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NUMERICAL METHODS IN WEATHER PREDICTION: I. THE BALANCE EQUATION*

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ABSTRACT

Two methods of solving the balance equation are outlined. Both methods have been used successfully on a daily operational basis at the Joint Numerical Weather Prediction Unit for a period of more than a year. Solutions were on the operational grid of 30 x 34 points spaced at 381-km. intervals.

1. INTRODUCTION

The Joint Numerical Weather Prediction Unit has been solving the balance equation on a daily operational basis for over a year on a grid covering more than 100,000,000 km.^{2} of the earth's surface (Shuman [1]). With this record of operations, it may safely be concluded that the methods used will never fail to yield a solution nor behave badly for any meteorological data. In view of difficulties anticipated in the literature concerning the solution of the balance equation on grids comparable in size to that used by the Unit it is felt that a record of our methods will be of some interest.

2. THE BALANCE EQUATION IN POLAR STEREOGRAPHIC SPACE

Perhaps the most common form of the balance equation is, in tangent plane coordinates,

$$f(\psi_{xx}+\psi_{yy})-2(\psi_{xy}^2-\psi_{xx}\psi_{yy})+(\psi_x f_x+\psi_y f_y)-g(z_{xx}+z_{yy})=0 \quad (1)$$

where f is the Coriolis parameter, ψ is the stream function, g is acceleration of gravity, and z is the height of an isobaric surface. The usual transformation of equation (1) onto the polar stereographic projection is

$$m^2f(\psi_{xx}+\psi_{yy})-2m^4(\psi_{xy}^2-\psi_{xx}\psi_{yy})+m^2(\psi_x f_x+\psi_y f_y)-m^2g(z_{xx}+z_{yy})=0 \quad (2)$$

where m is the map scale factor,

$$m=\frac{\rho_e^2+\rho^2}{2\rho_e r},$$

ρ is radial distance on the projection from the pole, ρ_e is radial distance on the projection from pole to equator, and r is the radius of the earth.

Equation (1), being in tangent plane coordinates, is not a rigorous expression of the dynamic laws, nor is equation (2) a rigorous transformation of equation (1) into polar stereographic space. Because serious questions have arisen in the past concerning possible inconsistencies between the common forms of the balance equation and the true physical laws the forms are meant to express, the balance equation has been derived from the equations of motion in spherical coordinates, and transformed rigorously into Cartesian coordinates on the polar stereographic projection. The derivation and transformation being lengthy, they will not be reproduced here for lack

*This is the first of a series of three articles on the subject of numerical methods of prediction used by the Joint Numerical Weather Prediction Unit.

of space. The resulting form is

$$\frac{1}{2}\,[m^2(\psi_{xx}+\psi_{yy})+f]^2-\frac{m^4}{2}\left[\psi_{xx}-\psi_{yy}+\underline{\frac{4\rho}{\rho_e{}^2+\rho^2}\cdot\frac{-y\psi_y+x\psi_x}{\rho}}\right]^2-$$
$$\frac{m^4}{2}\left[-2\psi_{xy}+\underline{\frac{4\rho}{\rho_e{}^2+\rho^2}\cdot\frac{-x\psi_y-y\psi_x}{\rho}}\right]^2+$$
$$m^2\left[\psi_y f_y+\psi_x f_x-\underline{\frac{\psi_x{}^2+\psi_y{}^2}{r^2}}\right]-\left[m^2g(z_{xx}+z_{yy})+\frac{1}{2}f^2\right]=0$$

where x and y are measured on the projection from the pole. The underlined terms, which are not implicit in the common form (2), are small. With the view to assessing them for integrated consistent effects, the balance equation was solved for one case with them included. Their effects proved trivial, so they will be ignored. We have then

$$\frac{1}{2}\,[m^2(\psi_{xx}+\psi_{yy})+f]^2-\frac{m^4}{2}\,(\psi_{xx}-\psi_{yy})^2-2m^4\psi_{xy}{}^2+$$
$$m^2(\psi_x f_x+\psi_y f_y)-\left[m^2g(z_{xx}+z_{yy})+\frac{1}{2}f^2\right]=0 \quad (3)$$

Equation (3) is a simple rearrangement of equation (2). For the purposes of the following discussion, it will be convenient to retain the balance equation in the special form (3). The boundary condition presently used is that suggested by Bolin [2]:

$$\frac{\partial\psi}{\partial s}=\frac{g}{f}\frac{\partial z}{\partial s}-\frac{\oint\frac{g}{f}\,dz}{\oint ds}$$

where s is distance measured counterclockwise along the boundary.

3. THE INITIAL PROGRAM FOR AUTOMATIC COMPUTING MACHINERY

The first method used on an operational basis was outlined in its essentials by the author [3]. It is a direct application of relaxation techniques [4] to the problem, and is similar to the method used by Bushby and Huckle [5] in their solutions of a modified balance equation.

One may write the finite-difference transformation of equation (3) in a rectangular mesh,

$$\eta^2-D_1{}^2-D_2{}^2+L-Z=0 \quad (4)$$

where η is absolute vorticity scaled so that the coefficient of the central value of ψ is -1, and $D_1{}^2$, $D_2{}^2$, L, and Z are appropriately scaled forms of the other terms in equation (3) in their order of appearance. It is to be noted that ψ at the central point is implicit only in the first term. It can be shown by variational calculus (e. g., Shuman [3]) that the differential equation (1) is elliptic if

$$g(z_{xx}+z_{yy})+\frac{1}{2}f^2-\psi_x f_x-\psi_y f_y>0$$

The corresponding condition for the finite difference equation (4) is probably

$$D_1{}^2+D_2{}^2-L+Z>0 \quad (5)$$

since no difficulty in treating it as a boundary-value problem has been encountered so long as the condition (5) is satisfied. However, since for meteorological data generally,

$$|Z|>>|L|$$

and since Z is almost exclusively positive, while $D_1{}^2$ and $D_2{}^2$ are positive definite, we first impose on the Z-field the condition

$$Z\geq 0 \quad (6)$$

by a technique that does not change its mean value nor, in practice, its large features significantly. The field of Z is scanned with a test for negative values. When a negative value of Z is encountered the values at the surrounding nearest four points are reduced by ¼ of the magnitude of Z at the central point, and the value of Z at the central point is increased to zero. Boundary values are excepted from change. A few scans are required to complete this operation.

In a numerical experiment involving some dozen cases, Mr. L. P. Carstensen of the development staff of our Unit has found that imposing the condition (6) implies only trivial changes in 500-mb. heights over areas of good data coverage, although changes of as much as 50 feet may be implied over areas of sparse data. It appears that the latter are due to analysis errors, due in turn to insufficient data.

Equation (4) may be written

$$\eta^\nu-[(D_1{}^\nu)^2+(D_2{}^\nu)^2-L^\nu+Z]^{1/2}=R^\nu \quad (7)$$

where ν is the scan count in the relaxation process, and R is a measure of the error of the current approximation. The Liebmann-type iteration is used, so that quantities designated by the superscript ν have only a brief existence. Specifically, the superscript ν denotes a value at a point during the ν-th scan after computation has been completed at the preceding point, but before computation has begun at the point in question. We will similarly write

$$\eta^{\nu+1}-[(D_1{}^\nu)^2+(D_2{}^\nu)^2-L^\nu+Z]^{1/2}=-\lambda R^\nu \quad (8)$$

Again, the quantity $\eta^{\nu+1}$ has only a brief existence. It is the value of η during the ν-th scan after computation has been completed at the point in question, but before computation at the succeeding point has begun. Thus,

$$\psi^{\nu+1}-\psi^\nu=-(\eta^{\nu+1}-\eta^\nu) \quad (9)$$

Equations (7), (8), and (9) may be combined.

$$\psi^{\nu+1}-\psi^\nu=(1+\lambda)\{\eta^\nu-[(D_1{}^\nu)^2+(D_2{}^\nu)^2-L^\nu+Z]^{1/2}\} \quad (10)$$

The quantity λ is the overrelaxation factor. It is to be noted that one cannot overrelax a residual based on

equation (4) as it stands, for with the little control one has over such an implied residual, and without D_1^2, D_2^2, L, or Z being bounded away from zero, one will surely encounter during the process imaginary values of η. On the other hand, the method of overrelaxation as indicated by equation (10) leads to no difficulty.

It has been found that the condition (6) is not always sufficient to satisfy the "elliptic" condition (5). At points where the other terms of the expression (5) are small, sometimes L is sufficiently positive to violate the condition. This has been handled by substituting zero for the expression (5) where the condition is violated, and keeping a count of such points during the scan. When convergence is otherwise indicated in four successive scans during which the condition (5) is violated at some points, the program proceeds in a similar fashion as before, but if, where negative, the absolute value of the expression (5) is smaller than a small number (an increment of Z is used, corresponding to $0.1\bar{f}^2$) it is ignored. The program has never failed to converge under these circumstances. The number of points involved has always been at least two orders of magnitude less than the total number (1,020) of points in the grid.

A disadvantage, from the viewpoint of time required, of the system (10) over solutions of linear equations is obvious, for it indicates a square root must be taken. The Newton iteration is used in our machine program. In terms of scan count, however, the system converges as fast as linear systems, as can be shown by solution of equation (3) treated as a Poisson equation in z. The total scan count is about the same whether one solves the equation for z with $\bar{f}g^{-1}\psi$ as the first guess, or whether one solves the equation for ψ with $\bar{f}^{-1}gz$ as the first guess. Total scan counts with such a first guess for our 30 x 34 grid of 381-km. mesh length is 100 to 125 scans. Our convergence criterion is

$$\bar{f}g^{-1}(\psi^{\nu+1}-\psi^{\nu})\leq\tfrac{1}{4}\text{ foot}$$

where $\bar{f}$ is the Coriolis parameter at 45°. The program described above runs from 40 to 50 minutes on the Unit's IBM 701, including all input-output operations and other overhead.

4. A FAST METHOD

The method described in this section is, except in certain minor details, identical to a method arrived at independently by Miyakoda [6]. At the first writing of this paper, the author was unaware of Miyakoda's work.

The foregoing program was used on a daily operational basis from April 20, 1956 to January 30, 1957. On January 31, 1957 we instituted an operational code which cut the total running time to 25 minutes. More recently, we began using 12-hr. barotropic predictions of ψ as a first guess, which reduces running time to 18 minutes. In these later runs the relaxation itself is done in slightly more than 10 minutes, the rest of the time being occupied with input-output operations and other overhead, including checking and recovery procedures. In the new fast program, the square root indicated in equation (10) is taken only every 10 scans or so, it being otherwise held constant. We call this process "cyclic", a "cycle" consisting of the computations between the computation of the square root.[2] This procedure reduces the fundamental relaxation computation to the fastest possible; i. e., to that of a Poisson equation. The process may be stated symbolically,

$$(\psi^{\nu+1}-\psi^{\nu})^{\sigma+1}=(1+\lambda)\{\eta^{\nu,\sigma+1}-[(D_1^{\sigma})^2+(D_2^{\sigma})^2-L^{\sigma}+Z]^{1/2}\} \tag{11}$$

where σ is the cycle count. Instead of fixing the number of scans per cycle to a constant figure, which we now think would be a better procedure, we vary the convergence criterion, beginning with 64 ft. for the first cycle, and reduce it by one-half for each succeeding cycle until it reaches the value, ¼ ft., and then hold it constant. A cycle then consists of relaxation of a Poisson equation extending to indicated convergence. Ten to fifteen cycles are normally required for convergence, which is indicated by four successive cycles of one scan each. At the end, we have been requiring two scans indicating convergence with the older slower program described previously.

There have been occasional cases in which the new program has failed to converge. It had reached a near-perfect oscillation in which

$$\eta^{\sigma+1}-[(D_1^{\sigma})^2+(D_2^{\sigma})^2-L^{\sigma}+Z]^{1/2}=0$$

$$\eta^{\sigma+2}-[(D_1^{\sigma+1})^2+(D_2^{\sigma+1})^2-L^{\sigma+1}-Z]^{1/2}=0$$

This has been handled by halting the cyclic process after 32 cycles, and proceeding to convergence with the older program, which at that stage has taken less than 15 scans to accomplish. We have never encountered a case in which the new fast program diverges from the solution. The oscillation has been associated with small-scale irregularities in the analyses of z. When the field of z is treated to remove components with wavelengths of less than five grid increments, the oscillation does not occur. This is an empirically indicated way of avoiding oscillations in the process (11). It is thought that a better way would be to begin each cycle with a first guess which is a weighted average of the "solutions" from the previous two cycles. In this average one should weight the "solution" from the immediately preceding cycle very heavily, otherwise the rate of convergence would obviously be affected adversely.

5. REMARKS ON OTHER METHODS

One can linearize the balance equation before applying relaxation techniques, for example, as Bolin [2] has done.

[2] The cyclic concept is due to Mr. L. P. Carstensen, who first applied it to the balance equation in the form (1). He held constant during each cycle all terms except the first in equation (1). Some solutions were successfully obtained in this manner, but in some cases divergence from the solution was manifest. G. 'Arnason later showed on a theoretical basis the conditions under which such application of the cyclic procedure would diverge from the solution. Bushby and Huckle [5] reported failure for a similar scheme. 'Arnason's work has been submitted for publication.

His method is precisely equivalent to performing a single Newton iteration on the radical in equation (10) at each point during each scan. He sets $\lambda=0$. He has successfully solved the balance equation on a 500-point grid in this manner. As he has indicated his method as presented will fail for larger grids with strict convergence criteria unless he can arrive at a much better first guess of ψ than $\bar{f}^{-1}\, g\, z$. The reason for failure will be that as the grid becomes larger, the heights become a poorer estimate of the $\bar{f}\, g^{-1}\, \psi$-field, and overrelaxation will become necessary to keep running time down to acceptable limits. We have found that on a 19 x 29-point grid with a mesh length of 304.8 km., the balance equation can be solved in a reasonable time without overrelaxation, but on our operational 30 x 34-point grid with mesh length 381 km. it is not feasible to run the code to convergence from a first guess of $\bar{f}^{-1}\, g\, z$ without overrelaxation.

Due to the monotonic approach of the Newton iteration to the square root, Bolin's system, with $\lambda=0$, consistently under-relaxes. One could introduce overrelaxation into his system, but again due to the monotonic approach of the Newton iteration to the square root, such overrelaxation would not be overrelaxation in the usual sense. It is conceivable that one could correct this deficiency by adjusting the overrelaxation factor by empirical or statistical techniques, but here one is limited by the fact that if λ were to approach unity in his scheme, the Newton iteration itself would become divergent. An important test in this respect, is upon a trivial finite-difference field of one internal point. It is inconceivable that a system failing this simple test would succeed generally when applied to large fields.[3]

As mentioned previously, Bushby and Huckle [5] have successfully solved a modified balance equation, using a method essentially like that of our older program. Their grid was quite small, 256 points. It is in order to remark that they defined the balanced wind components as divergent, thus,

$$u=-f^{-1}\psi_y$$

$$v=+f^{-1}\psi_x$$

and derived a balance equation modified by the neglect of terms which inevitably arose from the space variation of f. The author has since pointed out elsewhere (Shuman [1]) that conventional use of the geostrophic approximation implies serious physical inconsistencies due to geostrophic divergence. The "balanced" wind fields of Bushby and Huckle largely retain the geostrophic divergence, so will produce no significant improvement in predictions over geostrophic wind fields.

In order to avoid explicitly the square root computation, Kasahara [7] has proposed the following cyclic procedure. He first sets down

$$(\nabla^2\psi^{\sigma+1}+f)^2-(D_1{}^\sigma)^2-(D_2{}^\sigma)^2+L^\sigma-Z=0$$

where σ is the cycle count. He then linearizes this equation by expanding the first term, thus,

$$[\nabla^2(\psi^{\sigma+1}-\psi^\sigma)]^2+2\,(\nabla^2\psi^\sigma+f)\nabla^2\,(\psi^{\sigma+1}-\psi^\sigma)+(\nabla^2\psi^\sigma+f)^2-(D_1{}^\sigma)^2-(D_2{}^\sigma)^2+L^\sigma-Z=0$$

and neglecting the first term in the expansion. Fixing those terms superscribed by σ, he solves the resulting Poisson equation in $\psi^{\sigma+1}-\psi^\sigma$. He proceeds thus for several cycles to convergence. It is not clear that the division necessary to form the forcing functions for the Poisson equations will remain bounded, but if this were the case, and if the method were to prove otherwise universally convergent for meteorological data, it would indeed be of considerable interest.

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[3] G. 'Arnason in a paper soon to be published, has developed a method by a linearization technique which does not suffer from an implied monotonic approach to the square root. His technique, with a slower scan than the fast method outlined in this article, requires fewer scans. From a first guess of a quality similar to a 12-hr. prediction, his method competes successfully with the fast method described in section 4. Perhaps more important in terms of lasting interest, he has proven convergence for his method.

AN EXPERIMENT IN AUTOMATIC DATA PROCESSING

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ABSTRACT

An experiment in the automatic preparation of input data for use in numerical prediction is described. The process includes the automatic recognition, identification, and decoding of the raw teletypewriter data up to the point where they are ready for use in objective analysis. The problems encountered and the methods used to attack these are described. Present methods of coding and communication are such as to impede progress in automatic processing of meteorological data. Suggestions are made for improved coding methods as well as for improvements in the methods of automatic processing used to date.

1. INTRODUCTION

From the first experiments in numerical weather prediction it became evident that the preparation of input data for the computation would be a major problem. The requirement for worldwide data dictates that widely varying sources must be used. The uncertainty of radio communication means that large masses of data containing many errors must be handled.

The initial approach to this problem consisted of hand conversion, plotting, and correction of the data (insofar as errors could be recognized). These data were then analyzed by hand so as to maintain vertical, horizontal, and time consistency. Final data were then read off from these analyzed charts into forms or directly punched, as read, into Hollerith-type cards.

The second approach to this problem consisted of taking the information from data observation points, organizing it manually, and punching it into cards for loading into the computer, an International Business Machine EDPM 701. The computer, either by a local least squares fitting [4] or by a successive adjustment of a first guess map [1], interpolates these data into information on a square grid suitable for numerical computations. Some evidence shows that this method produces superior starting data for numerical forecasting [4]. However, the hand preparation of data must be done under considerable pressure, and errors can easily get into the process in spite of methods of careful checking. There was not very much saving in personnel here, since keeping up with the teletypewriters on a three-level code on a small grid required a force of about six people during the rush period. In order to detect data errors it was necessary to plot the data simultaneously so that an analyst could estimate the credibility of each report.

This paper describes the latest experiment, in which the data are processed completely mechanically from the time of receipt as telegraph signals. The possibility of manual intervention is retained so that control is possible at each step of the process.

2. NATURE OF THE PROBLEM

Our present forecast models, as well as models of the foreseeable future, require input data which specify the wind and temperature fields with a rather large horizontal extent (in order to remove boundary errors to as great a distance as possible) and for a number of levels in the vertical. The exact number of levels in the vertical depends on the complexity of the models. In addition, precipitation forecasting would require a measure of moisture. Since the number of pressure surfaces that can reasonably be used in the vertical depends upon the horizontal coverage of the data, as discussed by Fjørtoft [2], Thompson [8], and others, a rather limited number of pressure surfaces defines the atmosphere to the refinement that can be reasonably used in large-scale forecasting. This means that at present the required data for numerical forecasting must be extracted from a vast amount of data that is not to be used. The usable part of the upper air data is at most only about one part in ten, at least for large-scale forecasting requirements. The remaining nine-tenths of the data are useful mainly for checking the accuracy of transmission of the one-tenth, by means of the hydrostatic relationship and by vertical consistency considerations. Better organization of the transmitting codes could provide for a proportionate reduction in the volume of data to be handled and also could provide for more direct and simpler checking for accuracy. A sample effort in this direction was proposed by Gilchrist and Cressman [3].

When the meteorological codes are considered for automatic handling, the following main difficulties occur:

(a) there is no simple positive identification of the start and finish of each message,

(b) the type of message is not clearly indicated,

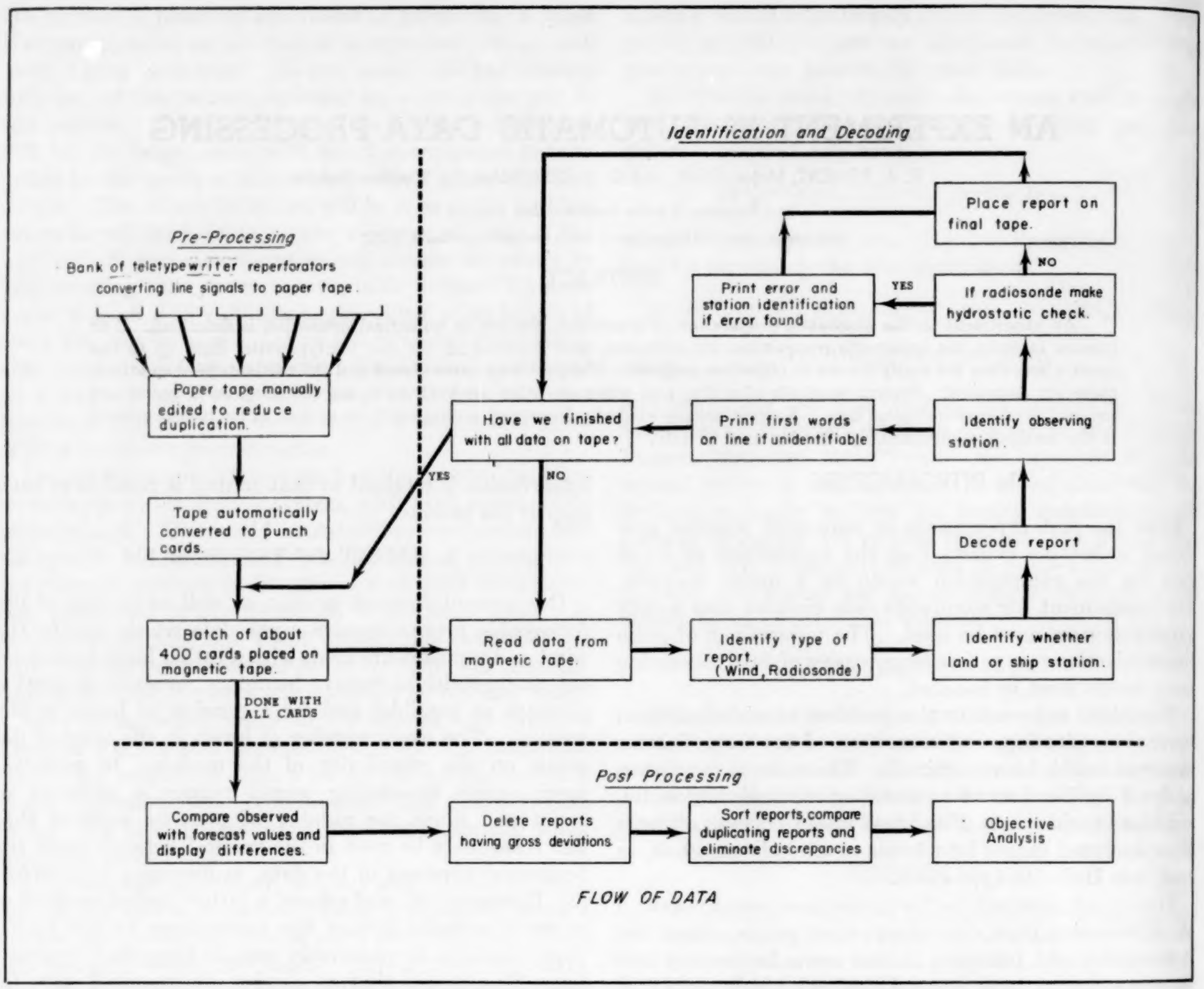

FIGURE 1.—The general flow in the operation of the automatic data processing program.

(c) an unnecessary number of local variations of code form is permitted,

(d) the station that took the observation can be identified in one of a number of forms,

(e) some of the station identifications, such as three decimal digit index numbers, are ambiguous if the headings are lost, and

(f) a large proportion of the message headings is lost or garbled.

3. DESIGN OF THE AUTOMATIC PROCESSING PROGRAM

The complete process of automatic data processing (ADP) is shown schematically in the flow chart, figure 1. The first two preprocessing items are done externally to the computer, as the data are being received. In order to receive complete upper-air coverage it is necessary to monitor about ten teletypewriter channels, thus contending with a great amount of duplication. Editing of the raw teletypewriter data is necessary to make the data manageable. Since the computer used here is designed for loading with punched cards, the teletypewriter tape is first converted automatically to cards, one card per teletypewriter line. This also makes possible the insertion of controlling cards to replace missing or badly garbled headings or other identification information. Since the present computer reads cards at 150 cards per minute and about 2,500 cards are required for Northern Hemisphere data, an appreciable amount of time in the program is required for loading. However, the problem does not quite justify the cost of off-line magnetic tape loading equipment. Figure 2 shows the equipment used in the generation of teletypewriter tape and the conversion from tape to cards. It was necessary to add more teletypewriter circuits (and reperforators) after this picture was taken.

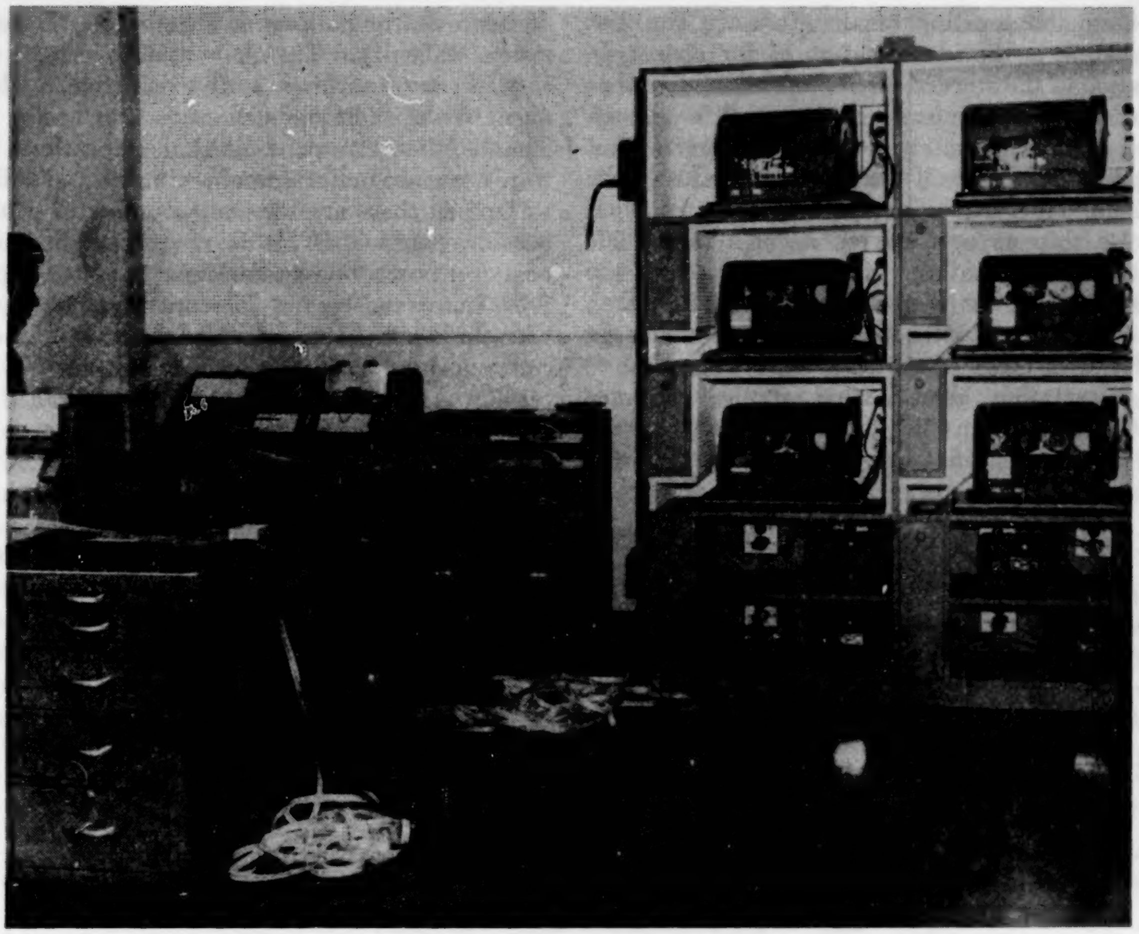

FIGURE 2.—Teletypewriter reperforators and tape-to-card converters in operation.

The design of the program is somewhat arbitrary and represents an attempt to see what can be done with a minimum of effort. First, it was decided that some control should be kept of the bulletin headings. Possible index numbers should be sought only in a limited list. The message headings are among the most carelessly prepared and most often deleted information on the circuits. It is therefore necessary to insert cards punched as pseudo-headings to mark places where the data change from one area to another without proper indication. A message heading ordinarily should contain a seven-digit word, the date-time group. The administration program therefore divides the lines into blocks each headed by a line containing a word greater than five digits. Each time more data are required, one of these blocks is read and the first line is examined to see if it is a message heading. If it is not, the long word is divided as if it were composed of accidentally run-together words.

There is provided a dictionary of stations consisting of a list of all the upper-air stations together with their call letters, if any, their index numbers, and their geographical locations. The dictionary is divided into three major parts. Part I contains the call letters of the fixed ships together with the units in which they report. Part II contains all of the stations which may have to be recognized by three-digit index numbers or by call letters. Stations in the area can also be recognized by five-digit index numbers, if under the proper heading. Part II is subdivided into sixteen parts. This reduces the searching time for finding something within an area, and partitions all of the duplicate index numbers such that if the area is identified correctly each three-digit number is unique. Part III contains all of the stations which may be looked up by five-digit index numbers regardless of message heading. They are confined to Europe, Africa, and Asia.

As each heading is recognized, the appropriate area in Part II is designated. The only search outside this preselected area that is permitted is in the case of two- and three-digit call letters. If one of these is found the dictionary control is shifted to the appropriate area.

One of the reasons for this strict control is that numerical identifiers are not unique and can easily be confused with data. There are many upper-air stations with common three-digit index numbers. Five-digit numbers can be confused with data groups or with three-digit index numbers having an illegal time group. As a result of this strict control, stations that make unusual deviations from the codes are printed immediately for attention instead of being mislocated.

The internal part of the program is divided into two

parts, decoding and locating of the station. The first stage of decoding is the identification of the code type and the location of the start of the report. Each line that could potentially begin a message is examined far enough to determine that it definitely does or does not. If it passes the preliminary tests it has been determined to be an international upper wind report, a United States upper wind report, a ship upper wind report, or a radiosonde report. Also at this point the most likely word for the location identification has been determined. The search for the location identification starts from the message and works back toward the beginning of the line. Due to the automatic station identification system on some circuits, a station that transmits another station's message produces a double identification, the one closer to the message being the correct one.

4. DETECTION OF THE METEOROLOGICAL DATA

The preliminary tests consist of first examining a line for either a five-and four-digit word alternation (United States upper wind) or a sequential first-digit series in a line of five-digit words (international or ship upper wind). If these tests fail, and the line is composed mostly of five-digit words, the radiosonde tests begin. Here, we have a serious difficulty. The digits used to identify the mandatory pressure surfaces and which give a characteristic form to the radiosonde message are mostly ambiguous. That is, the same digits in similar locations in the data words can also indicate temperatures. No difficulty arises as long as there are the same number of words for each pressure surface. This is recognized in the approved code form by a rule we can refer to as the "spacing rule" [9]. Unfortunately not all countries pay attention to this with the result that ambiguities can arise in internationally exchanged upper-air data. Garbles also give a similar result. An additional problem arises from the fact that internationally exchanged reports do not have similar content. Some countries do not transmit 400-mb. data, while others transmit 600-mb. data. Also, the 1,000-mb. and 850-mb. temperature and wind groups may or may not be reported, depending on station elevation. The solution adopted was to scan the message in a forward direction for a group starting with either "40" or "30", the lowest unambiguous pressure surface indicators. If the group "55555", meaning end of part I of the sounding, is encountered first (as in dropsonde reports) a radiosonde

TABLE 1a.—*Code forms*

Code	Recognition Features	Difficulties
U. S. upper wind code	Alternation of 4- and 5-digit groups to 10,000 ft., 5-digit groups thereafter. The 5-digit groups are in a sequence 2, 4, 6, etc., starting with the elevation of the station.	Accidental 4-digit words occur elsewhere causing false starts.
International upper wind code	5-digit code in sequence 1, 2, 3, 4, 5, etc., starting with the elevation of the station. Each 10,000 foot level is headed by 9999X where X is the 10,000's unit.	Sequences of numbers sometimes occur randomly in the data.
Ship upper wind code	5-digit code similar to the above except that it contains two 5-digit groups containing the latitude and longitude.	Ship messages are very poorly identified. Sometimes they contain the word "ship," sometimes they have ship identifications, and sometimes the name of the ship. Since the locations of the ships are not known a priori they can be badly mislocated due to errors.
PISEL	An abbreviated wind message originating mostly in Europe containing only the standard levels.	Not used in the present procedure as most of the significant winds are repeated in the radiosonde message.
Radiosonde:		
1. Land Station without wind	Sequence 85, 70, 50, 40, or 85, 70, 60, 50, 40 occurs, in every other word. Ends in 55555. May not be a 40 but may have 30, 20.	All of the level identifiers except 40 can occur as possible temperatures.
2. Land station with wind	Sequence 85, 70, 50, 40, or 85, 70, 60, 50, 40 occurs in every third word. Ends in 55555. May not be a 40 but may have 30, 20.	Stations frequently mix these two codes—transmitting 3 groups per level to the end of the wind, then transmitting 2 groups per level.
3. Ship station with or without wind	Sequence as above except that the 1,000-mb. height is preceded by 00 instead of the time and there are at least two additional groups before the 1,000.	Ships are often poorly identified.
4. Mesran	Same as above except the extra information about significant points does not follow.	Due to the fact that the 1,000-mb. group is usually not complete and the 850 may not be complete, as well as the presence of unnecessary words, the location of the 70 indicator may vary from the 3d to the 10th word in line.
5. Dropsonde	Contains a group 71717 after the latitude-longitude groups and terminates at 50. Otherwise conforms to ship code.	
6. ABTOP	A very neat selected-level code with information in two groups per level. Has rigid spacing rules so that any level can be identified.	Code form must be identified by the word "ABTOP" in the heading.

TABLE 1b.—*Set of rules for distinguishing code forms*

I. Start with the first 5-digit number after the first word in the line.
  a. If one of the following 3 words is a 4-digit word, test for U. S. Pibal Code.
  b. If the following 3 words are 5-digit and the data originated from a ship,
    (1) If the third following word begins with 2 and the fourth following with 3, assume it is a ship pibal.
    (2) If not above enter the test for a raob (d).
  c. If the following word is 5-digit and the data originated from a land station,
    (1) If second following word has a first digit one greater than that of the first following word assume it is a land pibal.
    (2) If not above enter the test for a raob (d)
  d. If the following word is 5-digit and does not meet criterion b or c search 17 groups for the following in order of priority:
    (1) a 5-digit word starting 40,
    (2) a 5-digit word starting 30,
    (3) a 5-digit word 55555.

II. If any of the above are found examine the previous word, if it:
  a. Starts with zero, the third previous a 50, and the sixth previous either 60 or 70, then it is a raob with winds.
  b. Does not start with a zero, but the second previous starts with 50 and the fourth previous 60 or 70, then it is a raob without winds.

report is also recognized. If none of the above can be located within the possible number of words, the data are discarded as "junk" (irrelevant) and the next line is considered. If a radiosonde report is thus tentatively recognized, the report is scanned backwards until enough form is established for extraction of the relevant data.

The threshold at which sufficient form is established for recognition of a report can be set at any arbitrary level. It appears impossible to avoid completely the recognition of random numbers as data unless considerable form is demanded. On the other hand, a high threshold requirement for form means that some partially garbled but partially useful material is rejected.

A recent paper by Glantz [5] gives some striking illustrations of this difficulty. It can be seen that the problem of automatic processing of meteorological data is in many ways similar to that of automatic language translation [6].

Table 1a shows the principal features of the program in use. Table 1b shows a set of rules which is used to determine the code form, applicable to all of the codes except PISEL* and ABTOP*. At present PISEL is ignored because most of the winds outside of the United States also come with the radiosonde reports. ABTOP is identified by the word ABTOP at the head of the message, which brings a special program into play.

*PISEL=Abbreviated upper wind code for standard pressure levels.
ABTOP=Report cf geopotential, temperature, humidity, and wind at standard pressure levels.
Both originate mainly in Europe.

At this point a comment is in order about the simplicity of the ABTOP Code. This code has a rigid form making group identification unnecessary. Extra groups have been eliminated at the beginning of the message, the groups for each level forming a vertical column down the page. Errors due to garbling are controlled by the hydrostatic check.

Table 2a shows the principal location identifications that must be dealt with. Table 2b shows the rules for determining which word is to be looked up as the identifier for locations in North America, the Atlantic, and the Pacific. In Europe, Asia, and Africa a different set of rules is used, since five-digit identifiers are used almost universally.

In the second part of the decoding section the information for the standard levels is actually extracted. In the case of radiosondes a hydrostatic check is performed, checking data preparation errors as well as miscoding and communication errors. Winds could be checked for consistency with the levels above and below, but in this code they are required only to be consistent between the pilot balloon report and the radiosonde report. The main problems in this section are the problem caused by missing wind groups and the estimation of the missing first digit of heights in a report transmitted in whole meters.

At first, units were controlled by bulletin heading. Later as stations in the Pacific and Greenland changed to meters, each station had to be recorded individually in the

TABLE 2a.—*Station identification types*

Station identification	Source	Difficulties
4-letter calls	ICAO identifiers and ships	Hard to separate from accidental 4 letters produced by 3-letter call errors.
3-letter calls	U. S. reports and ocean stations	May be multiple identification as when one station transmits another message. A false digit is sometimes added making a 4-digit call. Ocean stations frequently are spread out into 3 one-digit words and the identification may be on the previous line.
2-letter calls	Canada	Same as above, neither of these can be mistaken for a data word. Sometimes false two-digit calls originate when radio operator's initials precede a report.
3-number index	U. S. reports and in some countries on their private collections. May be relayed this way.	Very dangerous if separated from message headings because there are many duplicate index numbers in different blocks. Also some stations include a time indicator with the 3-digit identifier which makes it look like a 5-digit identifier.
5-number index	Most international relays	Easily confused with 5-digit data words. Certain countries place the 5-digit identifier on the previous line. Some prefix 999 bl. It is not located uniformly.
Ships	All types of bulletins	Since their location is not known in advance coding errors can easily cause them to be mislocated.

TABLE 2b.—*Set of rules for identifying stations*

Indexing Rules for North America and Pacific including Japan
I. Start with the word before the first 5-digit number on the line after the first word on the line.
II. If the word under consideration is not the first word on the line and it is: (a) 5-digit word—back up on the line one more word. (b) 4-digit word—test to see if it is the word "Ship", otherwise back up one word. (c) 3-digit word containing letters—look it up in the list of call letters. (d) 3-digit word containing all numbers—look it up in the list of index numbers for the dictionary subsection. (e) 2-digit word containing letters—look it up in the list of call letters. (f) any other word—back up one.
III. If the word under consideration is the first word in the line and it is one of the following, Temp, Pilot, US, or UC, apply these rules to the second word, otherwise apply them to the first: (a) 5-digit call letters—unidentifiable. (b) 5-digit, first two are letters—look up the index numbers as 3-digit index numbers in the list for the dictionary subsection. (c) 5-digit, first three are letters—look up the letters in the call letters. (d) 4-digit, all numbers—unidentifiable. 4-digit, first letter "N"—try to decode as a ship message. 4-digit, other—delete the first letter and try to find the last three in the call letters. If not found then try as a ship. (e) 3-digit word containing letters—look it up in the list of call letters. (f) 3-digit word containing all numbers—look it up in the list of numbers for the dictionary subsection. (g) 2-digit word containing letters—look it up in the list of call letters. (h) 2-digit word containing numbers—unidentifiable. (i) Any one digit—unidentifiable.

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dictionary as to whether the report was in meters or feet. Also Russian stations, which had been reporting in decameters changed to meters, which helped conformity; but at the same time their winds are transmitted in meters per second.

5. IDENTIFICATION OF THE REPORTING STATION

The second part of the origin identification consists of actually looking up the station in the dictionary. Since the dictionary is by nature large it is kept on the magnetic drum in the computer. Looking up an entry is therefore somewhat slow, and is postponed until the last possible moment. Since alphabetic call letters are more nearly unique they are looked up whenever encountered. This is desirable particularly for ships. In case no entry can be found in the dictionary for a call letter or index number, a display is printed of the information on the line through the first five-digit number, together with reference information, which makes it possible to determine why the station was rejected, and the number of the original data card. This display is shown in figure 3. If the rejection is due to bad message headings the rejected cards can be put in another load together with the proper message heading and recovered. This display is very useful in monitoring for changes. For instance, when the Idlewild radiosonde started transmitting with the same three-digit index number as Ely it was discovered immediately. Likewise, when the Japanese converted their units to meters without a warning being received at the operating levels an outbreak of hydrostatic checks caused us to discover this without delay.

```
1   9 248   5 125        THIS NOT FOUND //8/2 82710


1  23  23  16  58        THIS NOT FOUND 61401 14082
2  23  57  16 300        THIS NOT FOUND 03946 14140
3 127 130 08 495      HYDROSTATIC CHECK                850 - 700 MB
4 148 148 +58  29     HYDROSTATIC CHECK                850 - 700 MB
5 178 178  10  67        THIS NOT FOUND 15653 15990
6 189 290   7 401        THIS NOT FOUND OTE 15970
7 189 306   7  67        THIS NOT FOUND AKN15 94  2104 21705


1   1  95   4 401        THIS NOT FOUND GGW COR US768 15513
2 149 149 72 202      HYDROSTATIC CHECK                850 - 700 MB
3 168 180 72 938      HYDROSTATIC CHECK                850 - 700 MB
4 293 293 72 240      HYDROSTATIC CHECK    LCH        1000 - 850 MB
5 326 327 72 280      HYDROSTATIC CHECK                850 - 700 MB


1   1   1  16 300        THIS NOT FOUND 13660 01814
2 212 212   8 215        THIS NOT FOUND NSYF 21303
3 212 212 +52  35     HYDROSTATIC CHECK                850 - 700 MB
4 253 253 +62  33     HYDROSTATIC CHECK               1000 - 850 MB
5 253 253 +62  33     HYDROSTATIC CHECK                850 - 700 MB
6 253 253 +62  33     HYDROSTATIC CHECK                500 - 400 MB


7 372 383   1 125        THIS NOT FOUND SALIN AS 10268
1  47  47 72 906      HYDROSTATIC CHECK               1000 - 850 MB
```

FIGURE 3.—An example of the rejection sheet on March 10, 1957. On each line from left to right is the following:

Column one, the number of the rejection within one load (the loads consisted of maximum of 400 cards to minimize the time required for recovery);

Column two, a card reference number for the last card identified as a message heading;

Column three, a card reference number for the last card that should have been a message number (these two references made possible the location of the report in the original data);

Column four, a number telling the dictionary area from 1 to 16 in which the code was searching, or in the case of hydrostatic checks it contains the block number of land stations or a "+" sign and the latitude of a ship station;

Column five contains a clue as to why the station was not found or, if a hydrostatic check, contains the index number of a land station or the longitude of a ship station; after the identification of the line is printed exactly what was not found or what levels failed to check.

Note that in this list only one failure occured at 500 mb.

6. POST-PROCESSING

After the information has been properly extracted, checked, and stored away, and the cycle has been repeated until all of the information has been treated, the end product is a magnetic tape which contains edited data. It still has much duplication, the data being in the order in which they were received. Large errors can still be in the data; for instance, a partially garbled report containing only 500-mb. data which makes a hydrostatic check impossible, or a ship reporting in the wrong octant of the globe, either of which might be accepted as good data. To control this a rapid pass through the data is made to compare each observation with the 12-hour forecast made from the previous observations. A visual display is made of the worst piece of data in each grid square. The data worse than some criterion are automatically deleted. Any piece of data can be eliminated at the discretion of the analyst. Unfortunately in the Pacific and near the western boundary of the forecast grid rather large forecast errors can occur even in the 12-hour forecast. A criterion of a deviation of 600 ft. or a 50-kt. vector error of the wind was set as the rejection point of the data. This automatically removes the worst data and if it does on occasion throw out a valid report provisions are made to reinsert these reports at the discretion of an analyst. The data are then sorted into geographical order, duplicate information is checked and deleted, and the material is ready for analysis.

7. GENERAL EFFICIENCY OF THE SYSTEM

This system has been in operation on a test basis for nearly a year. With practice the pre-operations can be carried on by one person and the monitoring and correction can be done by one analyst, who also supervises the preparation of control information.

The operation of this code on the 701 computer is of

marginal benefit. Due to the novelty of the operation and the lack of organization of meteorological data in general, the complete automatic system has been used only for 500-mb. data, although the output of the ADP program includes all the levels from 1,000 mb. to 400 mb. Considerable time is consumed because of the slow card-reading speed of the 701, which uses about half of the total running time. The large look-up tables had to be placed in the intermediate speed memory system, slowing the operation of the code considerably.

The whole process of handling a day's input cards requires about 40 minutes of computer time. On the new IBM 704 computer for the JNWP Unit this situation will be greatly improved. A higher speed card-reader will be available. Larger memory capacity will make it possible to keep the look-up tables more readily available, and experience derived from this first program will provide a program with a basically more efficient design. A further increase in overall efficiency will result from the eventual use of data from several levels instead of just one.

8. METEOROLOGICAL COMMUNICATIONS FOR AUTOMATIC DATA PROCESSING

A word should be said at this point about the experience this has given concerning the meteorological communications system. Traditionally meteorologists have added more and more communications onto an already overburdened system on the theory that the more information you have the better off you are. The communicators' solution to their problem has been to increase the speed of data transmission and to add more circuits bringing more and more information into centers. Manual editing of data to provide better selection at relay points is not a completely satisfactory solution because editors rehandling masses of data are responsible for many errors.

A proposed solution for this problem would be to make two types of collections on the originating circuits. One collection would be a standard-level type of abbreviated code, with very high priority, for worldwide dissemination. A model of this type of bulletin is the European ABTOP code originating from Frankfurt, which has a very high density of usable information. The second collection could contain significant point information and detailed wind information in the vertical (which loses interest the farther away it is transmitted) primarily for local distribution. This procedure could give the following benefits: (a) it could reduce the volume of data to be transmitted and could expedite the transmission of data at no increase in cost, (b) it could provide makeup time on the circuits allowing repetition of high priority bulletins if transmission conditions are poor, and (c) it could justify the use of a high-cost channel such as ocean cable to insure prompt data receipt.

A second problem for data processing is the handling of nonstandardized information. This is mainly a problem for the oceans, since data over most land areas seem quite adequate for large-scale analysis. Ship reports are very important for analysis, but frequently contain wrong positions or are otherwise mishandled, arriving in damaged form. This is partly due to the fact that they may be relayed through nonmeteorological channels to the weather circuits. Surface reports from merchant ships are notably so full of errors that it is necessary to keep logs on ships to rate their credibility. Reports from commercial aircraft are very useful on the Atlantic and vital on the Pacific, but are mixed in abbreviated plain language and the old POMAR code, and are nearly unreadable to plotters, to say nothing of the difficulties of preparing a machine code to handle them. One thing that is often overlooked in the resort to plain language is that meteorological reports are an international commodity and any comment in a noncoded form may be wasted when it gets into another language area.

A third problem involving communication is the present haphazard system of transmitting corrections when the sender has detected an error. Frequently in international communication these involve comments in French, English, etc., such as "first word third line should read." Proper codes should be provided for making these statements.

Finally, more conformity with the existing codes ought to be required by all participating countries. Numerous examples could be shown of the following defects: adding time groups to three-digit index numbers to produce five-digit numbers of which the first three rather than the last are the index; placing the identification on the previous line; splitting ship call signs into three one-digit words; unauthorized and unnecessary plain language such as "Temp Ships 4xx Raob First"; violation of the spacing rule for radiosonde reports; and many others. All of these deviations require special testing to prevent failures.

9. CONCLUSIONS

In summary, the first experience in automatic meteorological data processing shows that it can be accomplished, but that some desirable changes in the organization of the data could make the process much more efficient. Meteorological codes and communication practices were originally designed for manual operations and for a wide variety of uses. The advent of automatic data processing increases the need for greater specialization of communications and for greater regularity of procedure.

The availability of more advanced computing equipment together with the experience gained in the system described above will result in a considerably improved automatic data processing system within the next year. It is possible that by this time the results of automatic processing can be made available to others in addition to the processing unit itself in the form of concise, well-organized, and accurate bulletins.

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THE WEATHER AND CIRCULATION OF OCTOBER 1957 [1]

A Month with a Record Low Zonal Index for October in the Western Hemisphere

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1. BLOCKING AND LOW INDEX

Blocking and low zonal index were dominant features of the circulation during October 1957. That this was a continuation of a longer-period trend is indicated by table 1, which lists 30-day mean values of the 700-mb. zonal index for each month of 1957. This parameter, which expresses the strength of the temperate-latitude westerlies averaged over the western half of the Northern Hemisphere, was below its corresponding normal value for seven of the first ten months of the year.

A reflection of the anomalous nature of the circulation for the year is the fact that Billings, Mont., Pueblo and Denver, Colo., Dallas, Tex., and Tampa, Fla., each recorded more precipitation during the first ten months of 1957 than had been recorded at these stations during any previous calendar year of record. In sharp contrast, 10-month deficiencies in precipitation were the greatest of record at several locations in the Northeast [10].

Examination of the data in table 2 reveals that the zonal index for the mid-latitude westerlies at the 700-mb. level in the Western Hemisphere was at its lowest value for any October since comparable data were first computed in 1944. Willett [11] and Namias [6, 7] have described the general nature and chief characteristics of the low-index state. Many of these are to be found as features of the circulation for October 1957.

Concomitant with this state is the presence of high-latitude blocking or a split in the planetary westerlies. During October this blocking was entrenched most firmly over northern North America. The monthly mean chart at 700 mb. (fig. 1) shows the blocking as the ridge located over the Yukon and its attendant positive anomaly center of 350 ft. This anomaly was elongated east-southeastward with a second positive center of 260 ft. near Churchill on Hudson Bay.

The blocking character of the ridge over the northwestern portion of the continent of North America is seen quite clearly in the contours in figure 1, with a high-latitude ridge poised just north of the trough along the west coast of the United States. A portion of the broad band of westerlies in the central Pacific curved northward around the ridge, while the southern portion of the mid-Pacific westerlies curved southward through the trough along the California coast.

TABLE 1.—*Monthly mean values of the zonal index at 700 mb. (in meters per second) for the area 35° N.–55° N. and 5° W.–175° E.*

	1957	Normal	Departure from normal
January	10.6	11.8	−1.2
February	11.0	10.2	+.8
March	8.4	9.1	−.7
April	8.9	8.3	+.6
May	7.3	7.7	−.4
June	6.9	6.9	.0
July	6.8	7.2	−.4
August	6.6	6.8	−.2
September	7.2	7.8	−.6
October	7.3	9.5	−2.2

TABLE 2.—*Mean October values of the 700-mb. zonal index (in meters per second) for the area 35° N.–55° N., 5° W.–175° E., with normals and extremes*

Year	October zonal index	Departure from normal	Year	October zonal index	Departure from normal
1944	8.8	−0.7	1951	9.4	−0.1
1945	9.0	−.5	1952	10.4	+.9
1946	8.8	−.7	1953	9.8	+.3
1947	10.6	+1.1	1954	10.8	+1.3
1948	9.6	+.1	1955	9.8	+.3
1949	11.1	+1.6	1956	9.4	−.1
1950	11.0	+1.5	1957	7.3	−2.2

Normals (computed from [9]):
Normal for October: 9.5 m/sec.
Highest normal for any month: 11.8 m/sec. (January)
Lowest normal for any month: 6.8 m/sec. (August)
Extremes:
Highest observed index for any month since January 1944: 13.0 m/sec. (January 1946)
Lowest observed index for any month since January 1944: 6.0 m/sec. (May 1946, 1948, 1952)

This split in the westerlies and the resultant difluent region over British Columbia and adjacent Pacific waters locates the area of most pronounced blocking in the monthly mean pattern for October 1957. A second seat of blocking, weaker in character, may be seen near the 80th parallel north of Novaya Zemlya. The positive anomaly center of 140 feet was less intense and much smaller in area than its North American counterpart. The split in the westerlies associated with the block was also less pronounced. It is interesting to note the same out-of-phase relationship south of this block, with a middle-latitude trough extending southward through central Russia.

A minor closed anticyclone appears in figure 1 over Greenland, but it should be noted that no positive anomaly was associated with it. This cell was a remnant of blocking which persisted over the Greenland area throughout the period from May through September 1957 (see previous articles in this series). Above normal heights as-

[1] See Charts I-XVII following p. 256 for analyzed climatological data for the month.

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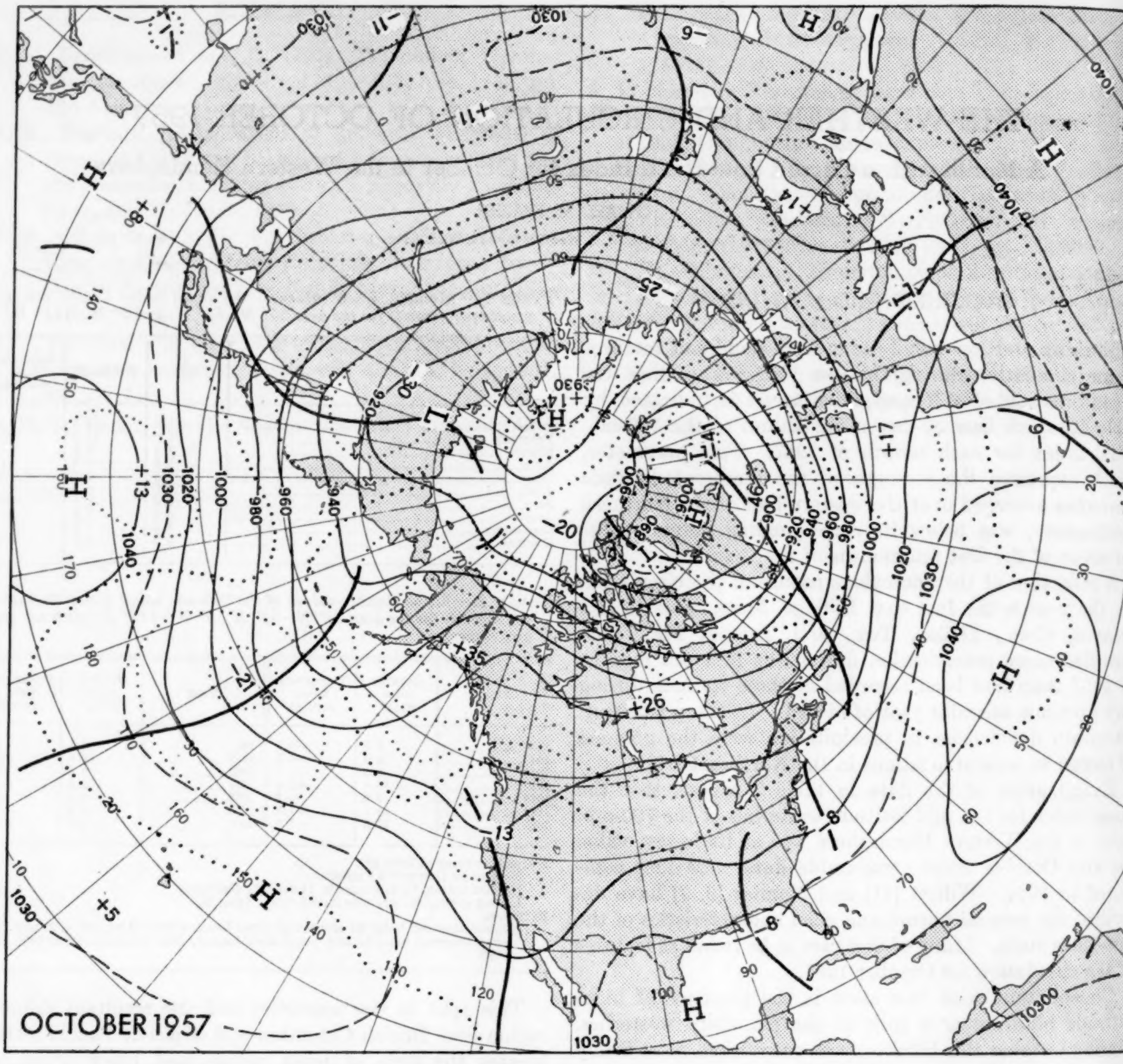

FIGURE 1.—Mean 700-mb. contours (solid) and departures from normal (dotted) (both in tens of feet) for October 1957. Note the diffluent nature of the westerly current emanating from the Central Pacific and the blocking character of the DN field over North America, with resultant weak westerlies over the United States.

sociated with the blocking High weakened rapidly during the early part of October and then disappeared completely as rapid deepening took place east of Greenland during the second week of the month.

A number of other features also reflect blocking and low index in October 1957. Figure 2, a profile of the westerly wind component from 20° N. to 90° N. for the Western Hemisphere, shows below normal westerlies in middle latitudes with above normal westerlies in both polar and subtropical regions. Namias [6, 7] has noted a tendency for the total momentum of the mid-tropospheric westerlies to standardize about a small range of values for a given month. This concept is portrayed in figure 2. The area under the normal curve (dashed) can be thought of as proportional to the total momentum of the westerlies, while the actual profile (solid) represents the latitudinal distribution of this momentum during October 1957. The total area under the solid curve was very nearly the same as the area under the dashed curve, and therefore the total momentum for October was conserved. The latitudinal distribution of this momentum varied markedly from the normal distribution, however.

Mean geostrophic wind speed isotachs are shown in figures 3A and 4 for the 700- and 200-mb. levels, respectively. At 700-mb. the split in the mid-tropospheric jet stream along the west coast of the United States was well

marked. Comparison with the normal jet stream for October (dashed) in this area shows a wind speed maximum from the central Pacific displaced progressively farther south of normal as it approached the west coast. There is weak but indecisive evidence in the original data from which the chart was drawn for continuing this axis of wind speed maximum across the United States near the 30th parallel, some 15°–18° south of its normal October latitude. A second wind speed maximum is present on figure 3A, beginning in northern Alaska and passing southeastward across Canada well north of normal. This split in the belt of strong westerlies over the North American continent was associated directly with the blocking character of the monthly mean circulation and was related to the anomalies of temperature and precipitation observed in the United States during October.

The contours and isotachs displayed in figure 4, the 200-mb. monthly mean chart for October, indicate the same general features as were observed at 700 mb., but in a less pronounced fashion. The split in the westerly stream along the west coast of North America was not as spectacular in the contour field at the 200-mb. level, but the isotach picture was comparable to that found at 700 mb., with a low-latitude jet stream across the United States and a second wind speed maximum at high latitudes.

Additional broad-scale features of the mean circulation for the month are observable in figures 1 and 3A. The largest anomaly of height at 700 mb. during October was the 460-ft. negative center located between Greenland and Iceland (fig. 1). This well-developed center of action was associated with faster than normal westerlies (fig. 3B) displaced north of normal (fig. 3A), as high index prevailed over the North Atlantic region during the month. It is interesting to speculate as to the probable relationship between the slower than normal middle-latitude westerlies associated with the North American block and the faster than normal westerlies and high index found over the Atlantic. The anomaly pattern in figure 1 is useful in rationalizing this relationship. The positive anomalies in height over Canada, especially those in central Canada, reflected an increase in the northwesterly flow over the Canadian archipelago. This flow conceivably transported more polar air than normal off the continent over the comparatively warm waters of the North Atlantic south of Greenland. As strong temperature gradients became established, baroclinic effects were probably related to the strong deepening which took place during the last three weeks of the month. Some measure of the intensity of the deepening is revealed by the fact that a daily system reached a sea level pressure close to 940 mb. on the 27th just to the northeast of Iceland. A second, and not completely independent, way of looking at the relationship between the circulation over North America and that over the Atlantic can be found by examination of the contour pattern over these regions in figure 1. As has been pointed out, the winds along the west coast of North America showed difluence as the westerly stream split to flow around a blocking High.

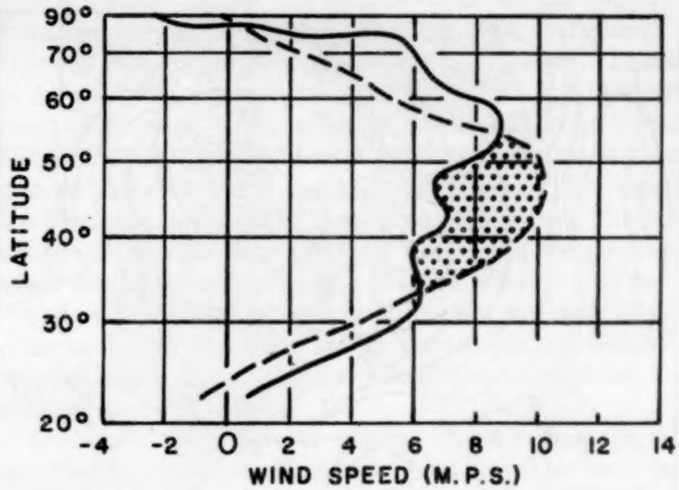

Figure 2.—Mean 700-mb. zonal wind speed profile for the Western Hemisphere for October 1957. The solid curve represents the observed and the dashed curve the normal for the month. Note how the decrease in speed of the middle-latitude westerlies was compensated for by an increase in the polar and subtropical westerlies, thereby tending to conserve the total momentum of the westerlies.

After passing around the block, the westerly current became confluent in character. Namias and Clapp [8] have discussed the mechanism for a speedup in the westerlies resulting from the type of confluent pattern portrayed off the east coast of the United States in figure 1 and implied in figure 3A.

In summary, then, the circulation of October 1957 was characterized by slower than normal 700-mb. westerlies over the eastern Pacific and most of North America. The belt of maximum winds was split over the continent with one belt displaced far to the south of normal and a second belt to the north of normal. A well-developed Icelandic Low and strong westerlies displaced north of normal were the main features of the circulation over the Atlantic.

2. THE MONTHLY CIRCULATION AND THE WEATHER ANOMALIES OVER THE UNITED STATES

The monthly anomalies of temperature and precipitation over the United States may now be related to the circulation picture. Charts I–B and III–B portray the departure of average temperature from normal and the percentage of normal precipitation for October 1957.

TEMPERATURE

Temperatures over nearly all the United States averaged below normal for the month. Table 3 lists a selected group of stations compiled to demonstrate the nearly nationwide extent of the abnormally cool temperatures. While only one station (Richmond, Va.) reported the month as the coldest October of record, the fact that much of the greater portion of the country experienced significantly below normal temperatures is a reflection of the abnormality of the mean circulation for the month.

The fact of unusually low index in the mid-latitude, upper-level westerlies indirectly indicates a mechanism

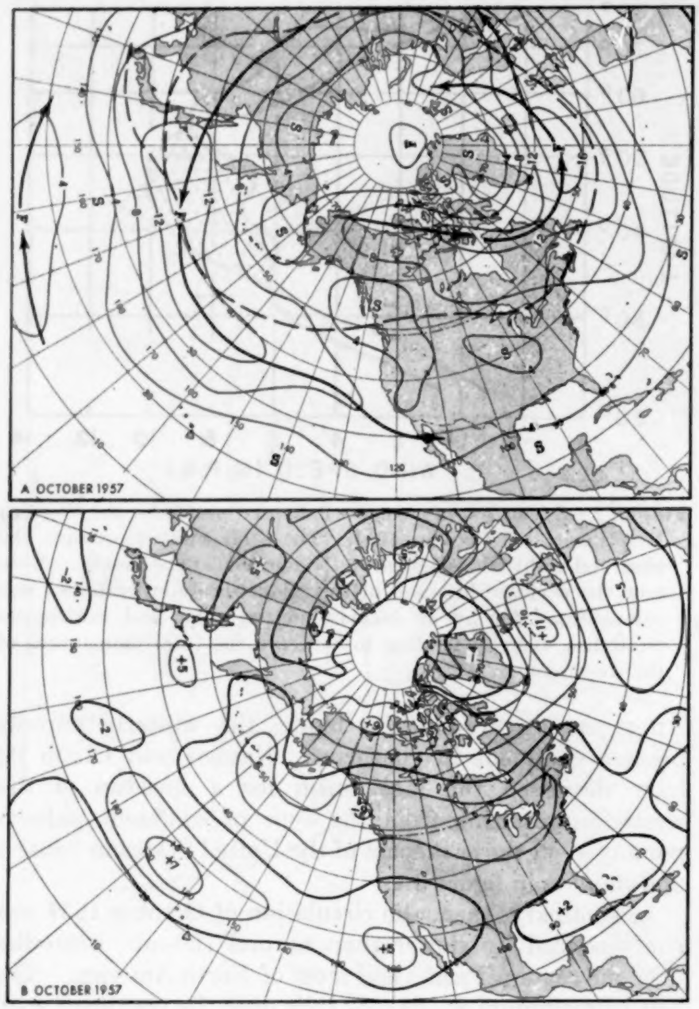

FIGURE 3.—(A) Mean 700-mb. geostrophic wind speed (meters per second) for October 1957, (B) Departure from normal of wind speeds shown in A (analyzed for 4 m/sec. except where otherwise indicated). Solid arrows indicate primary axis of 700-mb. jet stream and dashed arrows the normal October position.

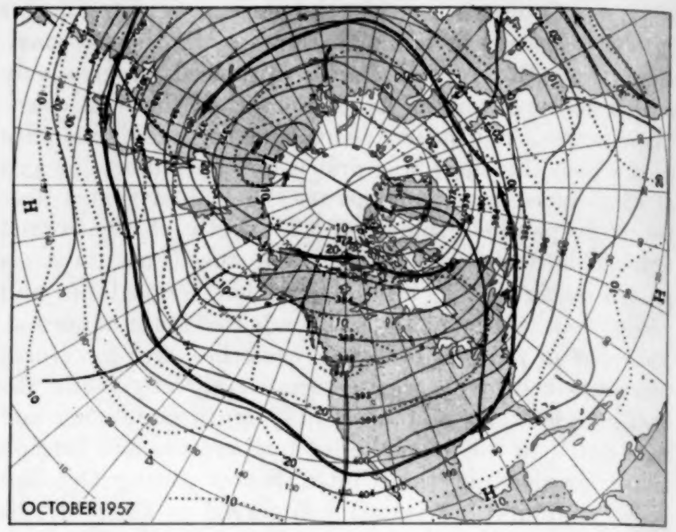

FIGURE 4.—Mean 200-mb. contours (solid, in hundreds of feet) and isotachs (dotted, in meters per second), for October 1957. Solid arrows give location of primary jet stream. A pronounced split in the jet stream over North America is evident.

for the deployment of polar air into the United States. A more direct indication may be found in figure 3A. The normal position of the jet stream at 700 mb. for October lies along the United States-Canadian border [4]. In this position the fast westerlies are effective in preventing meridional transport of polar anticyclones. Absence of a fast band of westerlies across the central portion of North America during October 1957, conversely, permitted periodic outbreaks of cold polar air over the country.

Comparison of the temperature anomalies depicted on Chart I–B and the departures from normal (DN) height (fig. 1) indicates a positive relationship between these two parameters over most of the country. Martin and Leight [5] found the positive correlation between these two parameters to be only moderately good during the fall season and obtained the poorest results along the west coast. During October 1957, the immediate coastal section of California and the Olympic Peninsula in Washington showed negative correlation (above normal surface temperatures and below normal 700-mb. heights). This underlines the importance of purely local effects and demonstrates the restraint necessary in attempting to relate all weather anomalies to broad-scale (both time and space) circulation patterns. In this particular area there is an apparent tendency for the coastal region temperature anomaly to be related inversely to that over the interior sections. This, in turn, has been associated with a strengthening of the sea breeze regime resulting in cool temperatures along the immediate coast when inland temperatures are above normal, with the reverse prevailing when interior temperatures are below normal.

Positive correlation exists between the above normal temperatures observed over New England in October and the above normal heights at 700 mb. It is difficult, however, to explain the above normal temperatures over New England on the basis of the sea level monthly mean

TABLE 3.—*Average monthly temperatures dand epartures from normal (°F.) for selected stations in the United States during October 1957*

	Temperature		Remarks
	October average	Departure	
FAR WEST			
Walla Walla, Wash.	50.4	−4.8	Coldest October since 1919.
Red Bluff, Calif.	60.0	−5.1	Coldest October since 1920.
GREAT PLAINS			
Omaha, Nebr.	51.8	−3.7	5th coldest October since 1900.
El Paso, Tex.	62.4	−2.8	Coldest October since 1912.
SOUTHEAST			
Fort Myers, Fla.	73.6	−2.7	Equals coldest October since 1913.
Birmingham, Ala.	58.5	−5.2	2d coldest October since 1900.
OHIO VALLEY			
Evansville, Ind.	54.1	−5.2	4th coldest October in 61 years.
MIDDLE ATLANTIC			
Elkins, W. Va.	46.9	−4.8	2d coldest October since 1900.
Richmond, Va.	54.6	−4.2	Coldest October in 61 years.

chart (Chart XI) and its departure from normal for the month (Chart XI inset). These charts show a mean sea level flow from the northwest and a northerly anomalous flow for the month, and thus imply advection from a relatively cool source region. The answer to this apparent discrepancy may lie in the fact that mean virtual temperatures in the 1,000–700-mb. layer over eastern Canada averaged as much as 3°–4° above normal during the month, and therefore the flow depicted over New England on Chart XI was from a region that was warmer than normal during the month.

PRECIPITATION

The difficulty in relating a discontinuous phenomenon such as precipitation to a mean pattern is well known. Chart III–B can be related to the mean 700–mb. and sea level circulations (fig. 1 and Chart XI) only in a gross sense. The location and amplitude of the mean trough along the west coast of the United States may be assumed responsible for the production of the well above normal precipitation amounts observed over most of the western two-thirds of the nation (as much as 700 percent of normal in parts of Arizona and Colorado). West-northwesterly flow from the Continental Divide eastward across the northern third of the nation and concomitant anticyclonic curvature tended to inhibit precipitation from the Dakotas eastward through the Great Lakes. The two weak mean troughs in the eastern third of the country (one in the Southeast and the other off the east coast) served only to provide a clue toward a complex rather than a simple precipitation pattern in this broad area.

In a gross sense the low-index pattern present during the month may be associated with the precipitation anomaly depicted on Chart III–B. The southward displacement of the mid-tropospheric jet stream (fig. 3A) was effective in transporting more moisture than normal from the Pacific into the Southwest and also in streaking moisture from the Gulf of Mexico eastward over the Southeast. At the same time, stronger than normal westerlies at low latitudes might have been expected to cut off the Gulf of Mexico as a moisture supply source for the region from the Central Plains eastward to the Atlantic Coast.

This same argument may be used to explain the highly anomalous character of the precipitation during the first ten months of 1957, mentioned in section 1.

3. TROPICAL ACTIVITY

During the past 70 years the Atlantic region, including the Gulf of Mexico and the Caribbean Sea, has averaged about two tropical storms per year in October, with about one of these reaching hurricane intensity [2]. One tropical storm did develop during the month, and its track may be found on Chart X beginning near 25° N., 60° W. on the 23d. Figure 9A is the 5-day mean chart at 700 mb., centered a day after the storm first made its appearance.

Six storms were observed over the tropical regions of the North Pacific during the month, with all six reaching hurricane (typhoon) intensity. Dunn [2] gives the normal October tropical storm frequency for the North Pacific as 4, with 3 occurring west of 170° E. and 1 off the west coast of Mexico. The increased tropical activity in the North Pacific this year was a reflection of greater than normal occurrence off the Mexican coast. This region has been unusually active throughout the season, but precise statistics regarding the total number of storms must await final tabulation. The increased activity was associated with the trough along the west coast of North America which has been rather persistent and well developed, especially at the lower latitudes, throughout the summer and fall seasons.

The tracks of the three storms which formed in the eastern Pacific may be found on Chart X. The first may have developed during September, as reported by Ballenzweig [1] in the previous article of this series. The second and third storms were generated during the latter half of October, and sparsity of data in the area necessitates the attachment of the label "preliminary" to their tracks and history. Apparently the storms passed near and over Mazatlan Mexico, although separated in time by only 24 to 36 hours and in space by only 60 to 80 miles. There is some evidence to indicate the first of the storms was dissipating rapidly before it passed inland.

Typhoons Irma, Judy, and Hester comprised the extent of the tropical cyclogenesis in the western Pacific during October, but tracks for these storms are not reproduced here. Irma developed west of the Philippines about the 9th and moved westward through the South China Sea, reaching typhoon intensity before passing inland over Indochina.

Hester was detected as a tropical storm on the 5th near 11° N., 145° E. It moved in a northerly direction during its life history, reaching typhoon intensity for at least 2 days before developing extratropical characteristics near 40° N., 150° E. some 350 miles east of Japan.

Judy was first detected as a typhoon on the 22d about 5° north of the position first given for Hester. The track followed by Judy, however, was northwest for about 48 hours, followed by recurvature just west of the 135° E. meridian, skirting about 150 miles east of the Japanese islands. The storm developed extratropical characteristics by the 26th in the area east of Japan and continued eastward and then northeastward across the Pacific as a well-developed system, finally becoming absorbed in the Aleutian Low.

4. FIVE-DAY MEAN CIRCULATIONS AND WEATHER OVER THE UNITED STATES

Data contained in table 1 denote a trend, on the order of months, in the zonal index of the mid-latitude westerlies. These data illustrate, on a basis of 30-day mean statistics, that the index has been at, or below, its normal value for six consecutive months. Computations based on longer- or shorter-period means, while not invalidating the facts in table 1, would, of course, present a different picture

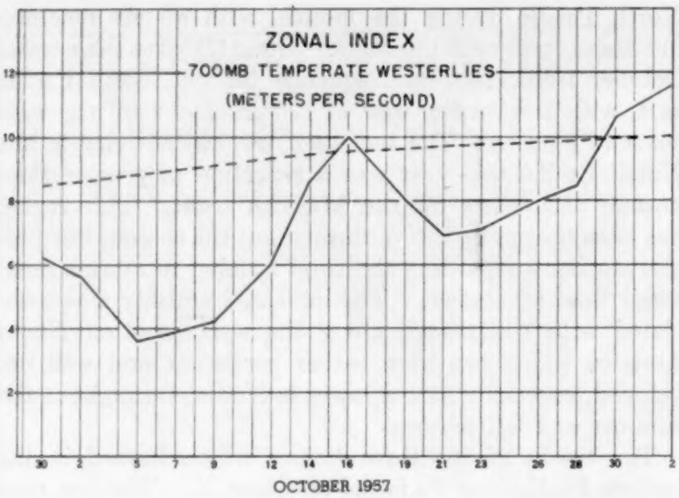

FIGURE 5.—Five-day mean zonal index of 700-mb. westerlies (35°–55° N.) for the Western Hemisphere, October 1957, with observed curve solid and normal dashed.

regarding the index. In routine extended forecasting a graph of 5-day mean index values (computed three times a week and plotted on the last date of the period) is prepared in addition to the 30-day index graph. The 5-day graph, as it applies to October, has been included here as figure 5 to assist in the discussion of the variations in the shorter-term mean circulations within the month.

Several conclusions regarding these variations can be obtained through this graph. It is evident from figure 5 that while the zonal index averaged below normal for October, it also underwent two oscillations during the month. Moreover, the trend of the index within the month was a return to more normal (higher) values.

FIRST WEEK

The 5-day mean circulation at 700 mb. for the period October 1–5 (figure 6A) represented the best developed low-index-type circulation of the month. The contour pattern with its large-amplitude waves and cut-off low centers at middle latitudes is characteristic of the classical low-index circulation. The DN field on this chart is even more expressive in depicting the interruption of the westerlies in mid-latitudes, with strong positive anomalies extending in a belt between 50° and 60° N. from the eastern Atlantic westward through the +500-ft. center in Canada to the +560-ft. center over the Alaskan Peninsula. A corresponding band of negative anomaly was found to the south, producing an easterly DN flow over much of the Western Hemisphere between 40° and 55° N.

The temperature and precipitation anomalies over the United States accompanying this classical low-index pattern are depicted in figure 6, B and C. The meridional orientation of the temperature anomaly, as well as its sharp gradient in an east-west sense, also fits the low index-large amplitude concept. The belt of above normal temperatures extending from New Mexico to the Dakotas was related to the mean ridge and its stronger than normal southerly flow shown in figure 6A. The colder than normal areas west of the Continental Divide lay under well below normal heights at 700 mb. as did the region east of the Great Plains.

Precipitation for the week as shown in fig. 6C was also related to the mean mid-tropospheric circulation of the week. The trough along the west coast, with its cutoff center over British Columbia, was effective in producing widespread precipitation over the West, although the dry weather over southern California is rather difficult to explain on this basis. Northerly flow and anticyclonic curvature at upper levels can be assessed as responsible for the precipitation void in the center of the country, while the cutoff Low in the Gulf of Mexico was responsible for the copious precipitation over the Southeast. Less precipitation over the Northeast may be related to the desiccating effect of the northwesterly and westerly flow dominating the region (fig. 6A).

SECOND WEEK

Rather spectactular changes in the 700-mb. circulation occurred during the second week of the month. Attention is directed toward a comparison of the DN fields in figures 6A and 7A in the area east of Greenland. The 610-ft negative anomaly centered near 60° N., 30° W. (fig. 7A) represents a deepening in this area of 830 ft. from the 5-day mean centered one week earlier.

Events leading to this deepening can be examined on a variety of time and space scales. The deepening was discussed on a broad-scale, monthly mean basis in section 1 and will now be related to the pattern of figure 6A. On this basis it is proposed that the deep polar vortex located near 80° N., 120° W., in association with the strong band of westerlies extending across northern Canada and Baffin Bay and the low center near 50° N., 50° W., provided shorter-term mechanisms necessary for the development of a strong baroclinic field just east of Greenland. Acknowledgement of a mechanism for development of a strong baroclinic field is not meant to deny barotropic support for the deepening which occurred.

The 5-day mean index of the zonal westerlies in the Western Hemisphere (fig. 5) responded to this deepening near Iceland as the westerlies increased at middle latitudes over the Atlantic.

No means for lowering the average temperature from the previous week by as much as 12° (compare figs. 6B and 7B) in the area east of the Continental Divide is readily discernible from figures 6A and 7A. At the surface was a strong polar anticyclone (see Chart IX) which moved southeastward from Alberta on the 7th and then slowly eastward across the northern part of the United States during the next 8 days. The contour pattern at 700 mb. (fig. 7A) provided an excellent steering current for this cold High, which, from the point of view of origin and slow movement, was sufficient to account for the sharp cooling over the Great Plains and the below normal temperatures observed over the country during this second week of the month.

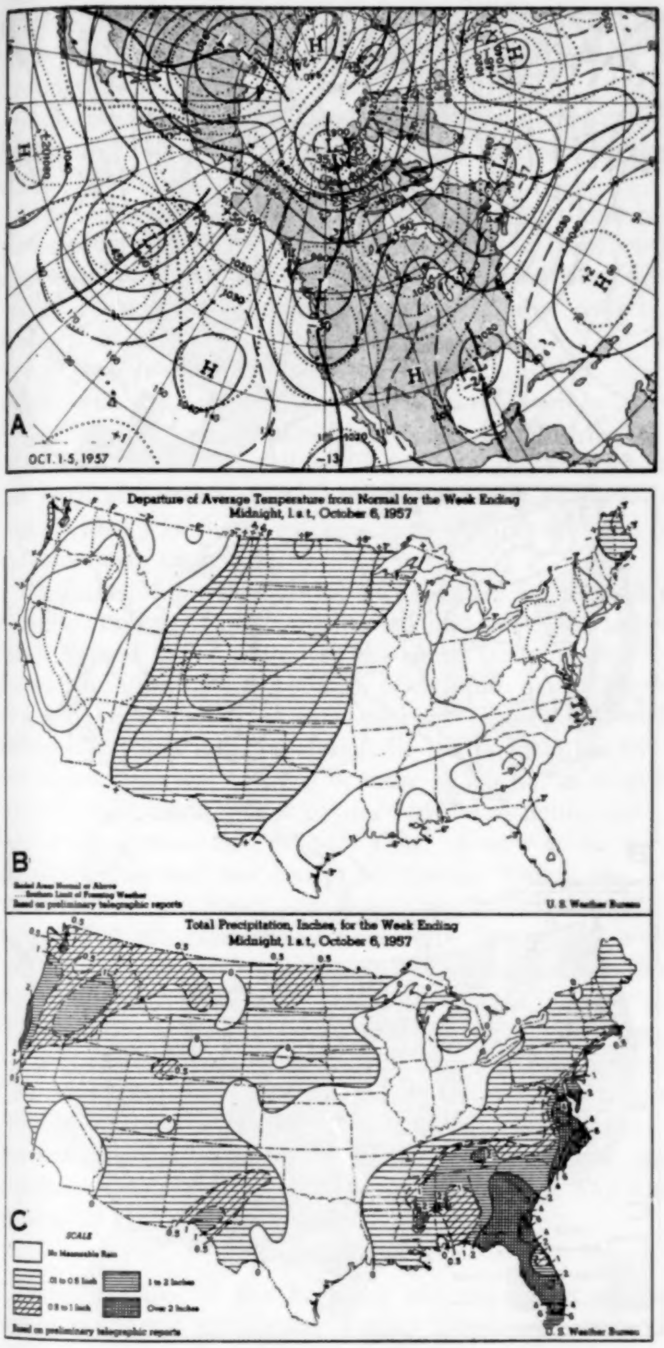

FIGURE 6.—Week ending October 5, 1957. (A) 5-day mean 700-mb. contours (solid) and departures from normal (dotted), both in tens of feet. (B) Surface temperature departure from normal (° F.). (C) Total precipitation (inches). B and C from *Weekly Weather and Crop Bulletin, National Summary,* vol. XLIV, No. 40, Oct. 7, 1957.

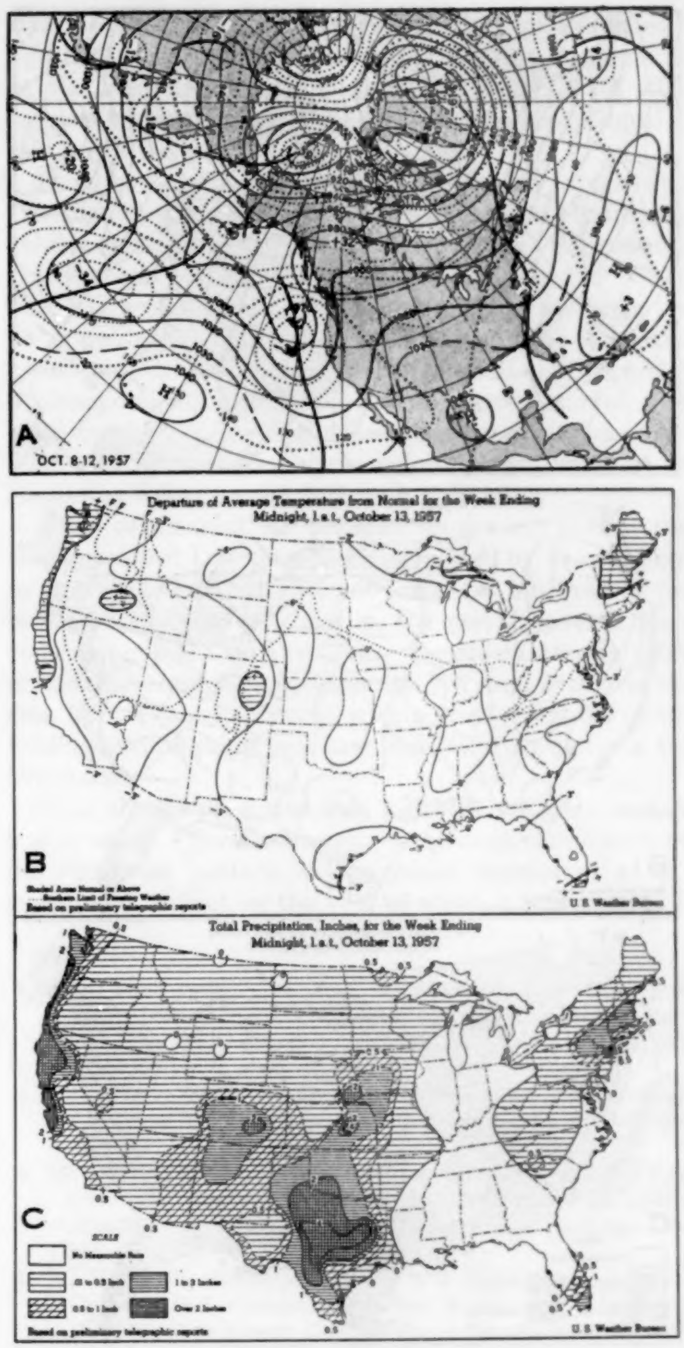

FIGURE 7.—Week ending October 12, 1957. (A) 5-day mean 700-mb. contours (solid) and departures from normal (dotted), both in tens of feet. (B) Surface temperature departure from normal (° F.). (C) Total precipitation (inches). B and C from *Weekly Weather and Crop Bulletin, National Summary,* vol. XLIV, No. 41, Oct. 14, 1957.

Heavy precipitation (fig. 7C) along the west coast can again be associated with the mean trough off the coast. The precipitation which occurred over New England was related to the mean trough at 700 mb. and the easterly DN flow over the area. The heavy precipitation in Texas was not related to the pattern portrayed in figure 7A but rather to a pattern which evolved from it. The heavy rainfall in this area fell on the 12–14th. Lack of concrete suggestions for heavy precipitation on a mean chart, centered 2–4 days earlier, points up some of the problems inherent in extended range forecasting in a rapidly evolving situation. In a daily sense, the precipitation in the Texas-New Mexico-Colorado region was produced as a frontal system moved eastward from the area of the mean trough shown off California on figure 7A. As it moved eastward a strong southerly current of warm moist air was advected northward from the Gulf of Mexico on the 10th and 11th. This system spawned at

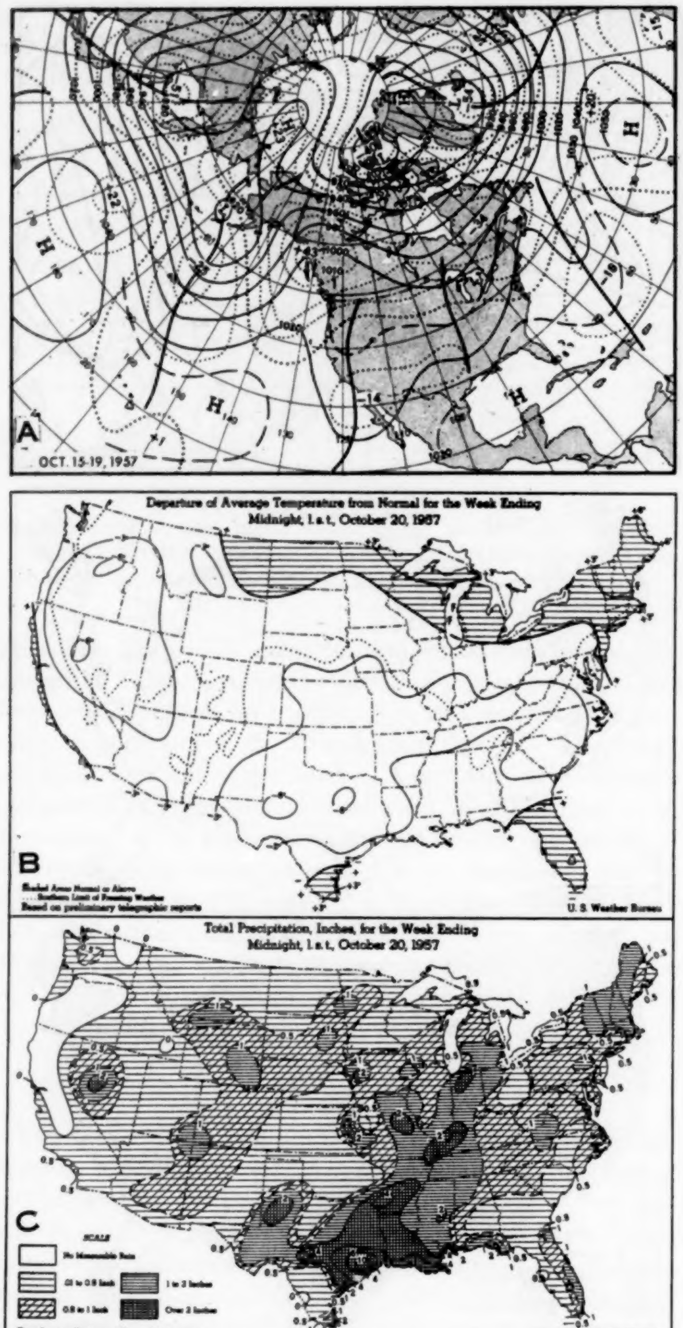

FIGURE 8.—Week ending October 19, 1957. (A) 5-day mean 700-mb. contours (solid) and departures from normal (dotted), both in tens of feet. (B) Surface temperature departure from normal (° F.). (C) Total precipitation (inches). B and C from *Weekly Weather and Crop Bulletin, National Summary,* vol. XLIV, No. 42, Oct. 21, 1957.

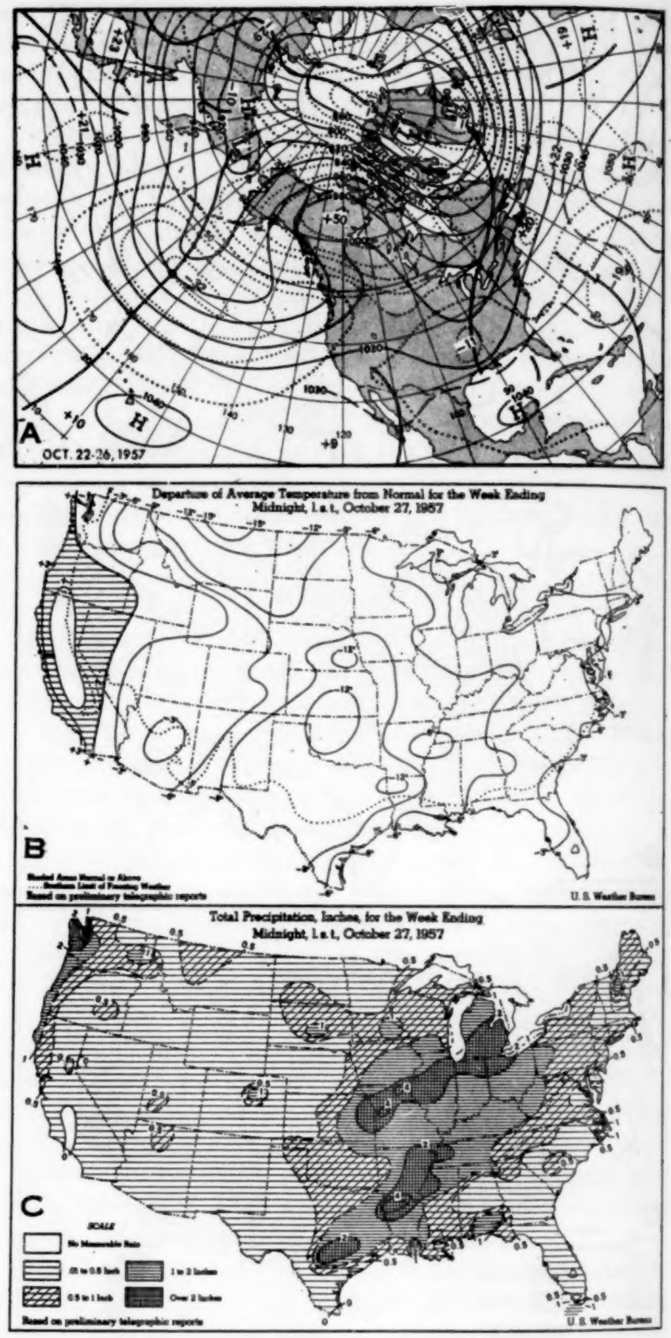

FIGURE 9.—Week ending October 26, 1957. (A) 5-day mean 700-mb. contours (solid) and departures from normal (dotted), both in tens of feet. (B) Surface temperature departure from normal (° F.). (C) Total precipitation (inches). B and C from *Weekly Weather and Crop Bulletin, National Summary,* vol. XLIV, No. 43, Oct. 28, 1957.

least one tornado on the 12th in New Mexico, two on the 13th in Texas and western Oklahoma, and still a fourth and fifth in Texas on the 14th as the daily trough system moved through the region.

THIRD WEEK

From figure 5 it can be seen that the second oscillation in the index of the zonal westerlies at 700 mb. began within the period of the 5-day mean chart presented as figure 8A. Positive height anomalies over Canada on this map were not materially different in either pattern or intensity from those shown in figure 7A. Intermediate-period 5-day mean DN charts (not shown) provide continuity for the +340-ft. center over eastern Canada and show that it was related to the +320 foot center over the Yukon in figure 7A. Similarly, the +430-ft. center just inland from the Gulf of Alaska can be tracked back to the +400 ft. center over the Alaskan Peninsula. This eastward rearrange-

ment of the seat(s) of blocking over North America took place while the large negative anomaly center east of Greenland remained nearly stationary. Deepening of the Asiatic coastal trough and the dispersion of energy downstream may have provided the means for eastward motion of the DN features over North America.

Aside from the deepening in the Pacific, the most important feature of the mean circulation of the third week was the introduction of a new trough over the central portion of the United States, as the wave number over the Western Hemisphere increased from 4 to 5. This increase in wave number resulted in an unusually short wavelength over the country and was responsible for a change in the precipitation regime observed during the first two weeks. Rainfall in Illinois and Indiana, which had been almost nonexistent during the first two weeks, became heavy in many sections with the introduction of the new mean trough.

Precipitation amounts recorded in figure 8C present a rather complex pattern, but, in a general sense, the larger totals appear to be related to the mean trough positions shown in figure 8A. Absence of rainfall over Oregon and northern California was probably associated with easterly DN flow and therefore drier than normal air over the region, but the 2 inches or more which fell in central Nevada may have been a product of the cyclonic curvature in the contour field over the area. Heavy amounts in eastern Texas and the Lower Mississippi Valley can be attributed to the mean trough and weak cyclonic curvature at 700 mb., but the southeasterly flow at sea level on a 5-day mean basis (not shown) provided the moisture which the upper-level convergence acted upon.

Temperatures showed great stability in pattern from the second to the third week, but warming was evident from Montana eastward through the Great Lakes to the Northeast. The similarity of pattern and sign between the anomaly of temperature during this week and the departures from normal of 700-mb. heights (fig. 8A) was great over much of the country.

FOURTH WEEK

Intensification of the blocking characteristics of the mid-tropospheric circulation during the fourth week of the month was reflected by the 580-ft. positive anomaly center over the northern Yukon (fig. 9A). This center reached a peak intensity of +710 ft. about 8° farther west during the 5-day period October 19–23 (not shown), near the second minimum point reached on the index graph (fig. 5).

Adjustment in the wavelength over North America occurred with this increase in the intensity and amplitude of the contour ridge at 700 mb. (fig. 9A). This adjustment was reflected most clearly in the marked sharpening of the trough over the eastern United States and its northeastward extension to Greenland. The west coast trough weakened somewhat in response to stronger mid-latitude westerlies in the Pacific and the superposition of the ridge to the north.

The Atlantic coastal trough, which had been a full-latitude feature in figure 7A, and sheared and weakened in figure 8A, was suppressed farther southward in figure 9A as the westerlies increased sharply to the north. The tropical cyclogenesis mentioned in section 3 developed in this mean trough.

Daily systems associated with the major trough from Greenland to Louisiana (fig. 9A) combined to produce the coldest weather of the month over much of the country. Cyclogenesis occurred over Colorado on the 22d (Chart IX). Grace and Bohl discuss the unusual movement of an upper-level daily system prior to the time it became associated with the surface development in another article in this publication [3]. The surface system moved eastward on the 23d, causing widespread precipitation in the Ohio and Mississippi Valleys before passing out the St. Lawrence Valley on the 24th and 25th.

Polar continental air plunged southward behind this well-developed Low on a track suggested by the contours in figure 9A, but full effect of the polar outbreak is not indicated in figure 9C, because the period covered there ends at midnight on the 27th. Record-shattering minimum temperatures occurred on the 27th and 28th over the area from Texas to Florida, with a goodly number of the readings establishing new low marks for so early in the fall season.

Thus, the month ended with a display of highly anomalous weather. Such a display was quite in character with the abnormal pattern of the mean circulation of the month and, in fact, of the year of which it was a part.

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MOVEMENT OF AN UPPER-AIR LOW OVER THE WESTERN UNITED STATES, OCTOBER 16–24, 1957

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1. INTRODUCTION

Early on the morning of October 16, 1957, a rather ordinary-looking trough aloft moving eastward arrived over the Pacific Coast in the vicinity of Vancouver Island, B. C. There it began to form a closed circulation at most of the intermediate levels. On the surface there was no associated Low nor frontal system and only a little weather.

This was the beginning of a cold Low aloft whose irregular movement in the succeeding seven days was to cause a series of consistently poor upper-air prognostic charts over the western United States by both the National Weather Analysis Center and the Joint Numerical Weather Prediction Unit.

It is the intent of this study to show what happened and insofar as possible to explain why—to show how the Low was actually forecast and evaluate some of the better known techniques that were or could have been used in its prediction.

2. MOVEMENT AND RELATED WEATHER

Figure 1 shows a sequence of 500-mb. charts at 24-hour intervals which span the period under study. It will be noted from this series that the Low reached its maximum intensity near mid-period when it was over central and southern California. At approximately the same time sea level pressures under the Low reached minimum values which permitted the only occasion in the sequence for a clear-cut analysis of a closed Low at the surface. The degree of deepening at sea level was about the same as that occurring at 500 mb., indicating that most of the deepening was due to warming at levels above. This was borne out by the observation of very little change in the mean virtual temperature field between 1,000 and 500 mb.

Tracks of the low center (fig. 2) at 500 and 200 mb., and of the cold core in the 1,000-500-mb. thickness, show very good similarity in both direction and speed. At 700 mb. the path was essentially that at 500 mb., but at 850 mb. the analysis of a closed center was too often questionable or impossible to allow tracking.

It will readily be appreciated that such erratic motion presented difficulties in predicting the track. Note in particular the abrupt change in direction and immediate acceleration at 0000 GMT on the 19th, the rapid deceleration at 0000 GMT on the 21st, and the nearly phenomenal acceleration again 24 hours later.

Surface weather associated with the vortex was neither severe nor record-breaking. The Low was, however, responsible for temperatures 3° to 6° F. below normal over a large portion of the West and for above normal rainfall in some sections, particularly western Nevada [1], a normally arid region. The relatively heavy precipitation in Nevada occurred at mid-period of the series while the Low was at its maximum intensity.

Perhaps more important than the surface weather in this situation were the winds aloft. Forecasts of winds aloft certainly must have been notably poor for periods in excess of 12 hours and at certain critical times and localities.

3. CONTRIBUTING CAUSES AND EFFECTS

In attempting to explain what caused the Low to move as it did one must, as in most similar meteorological matters, view the problem completely by hindsight.

One of the first factors to be considered is that of the tendency field. Dashed lines in figure 1 show the height change in 200-ft. intervals at the 500-mb. level for the 12-hour period immediately preceding the individual chart. It will be noted in figure 1A that the centers of rising and falling heights were very nearly in a west-east line, with rises to the west and falls to the east indicating eastward motion. In figure 1B the orientation has become northwest-southeast with the tendency component contributing to motion toward the southeast. In figure 1C, although not readily evident, the rise area previously lying to the northwest has split, leaving one cell northwest of the center while the other has moved to the northeastern sector. This was quickly ascertained from the 1200 GMT analysis which revealed the rise center at a position directly north of the fall center with protuberances toward the southeast and southwest. It will also be noted in figure 1C that the fall area has diminished about 200 feet. This stage left two tendency vectors, both of lesser magnitude than before, one directed toward the southeast and the other toward the southwest. In figure 1D the fall area east of the center has disappeared and a new region of fall has appeared to the west-southwest giving vectors directed toward the west-southwest and the south. Refer-

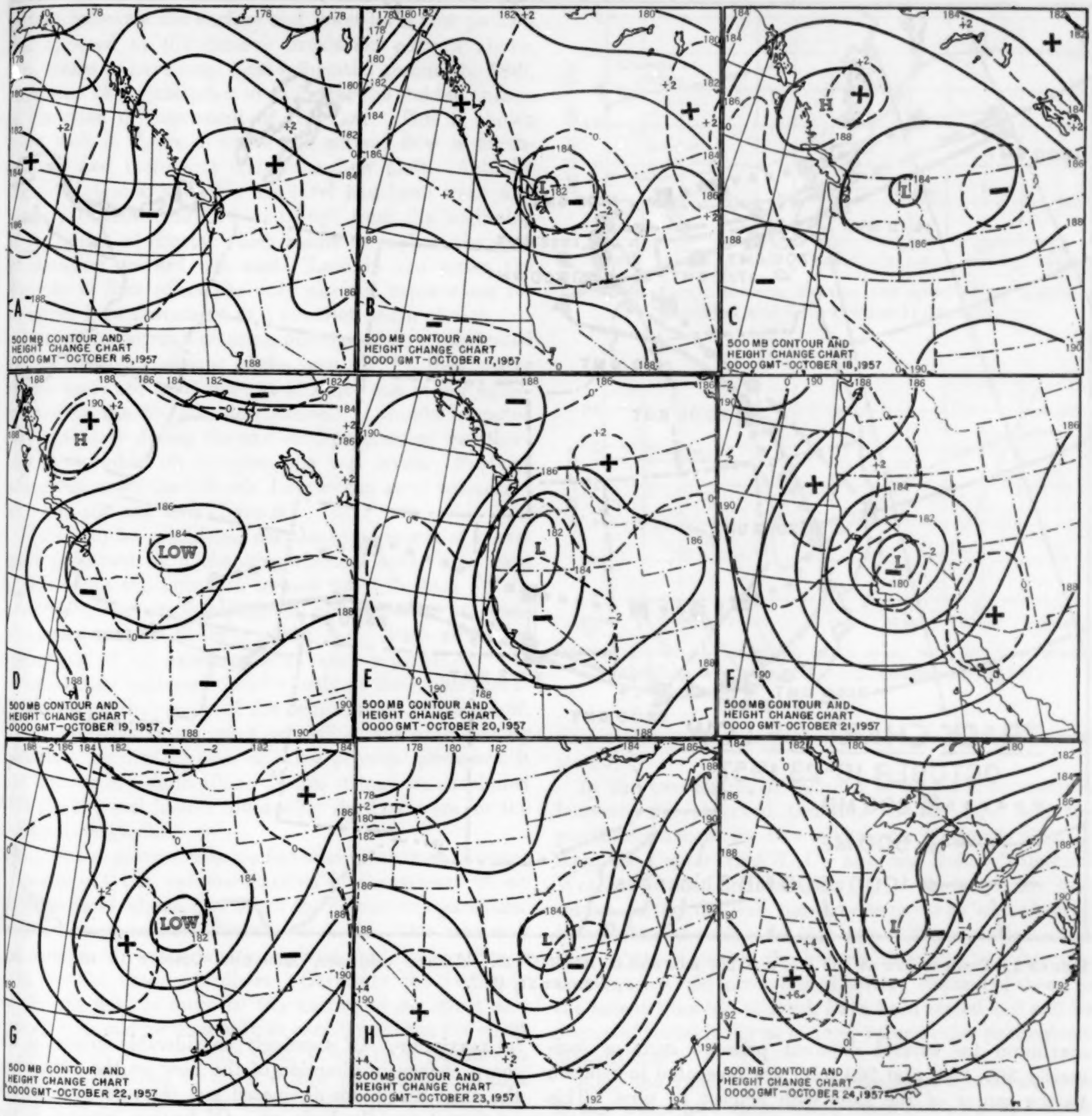


FIGURE 1.—Series of 500-mb. charts and 12-hour 500-mb. height changes (dashed lines, hundreds of ft.) showing location and configuration of Low and change areas at 0000 GMT, October 16–24, 1957.

ence again to the track chart (fig. 2) shows that the Low reached its easternmost extremity at this point before turning back. In the remaining charts of figure 1, it can be seen that the tendency vector indicated very well the instantaneous direction of movement. Of further interest is the intensification of the change fields toward the end of the series while the Low was actually weakening. This could be correlated with only a much more rapid movement of the system.

Still another element to be considered in explanation of the path taken by the Low is the overall steering effect of the current in which the Low was embedded. This, of course, entails study of the current in various quasi-horizontal planes which must in the end be combined to include also those forces acting vertically.

First let us examine the effects of the jet stream and of the jet maximum in that stream. In figure 3 a more or less combined or averaged position and speed of the jet

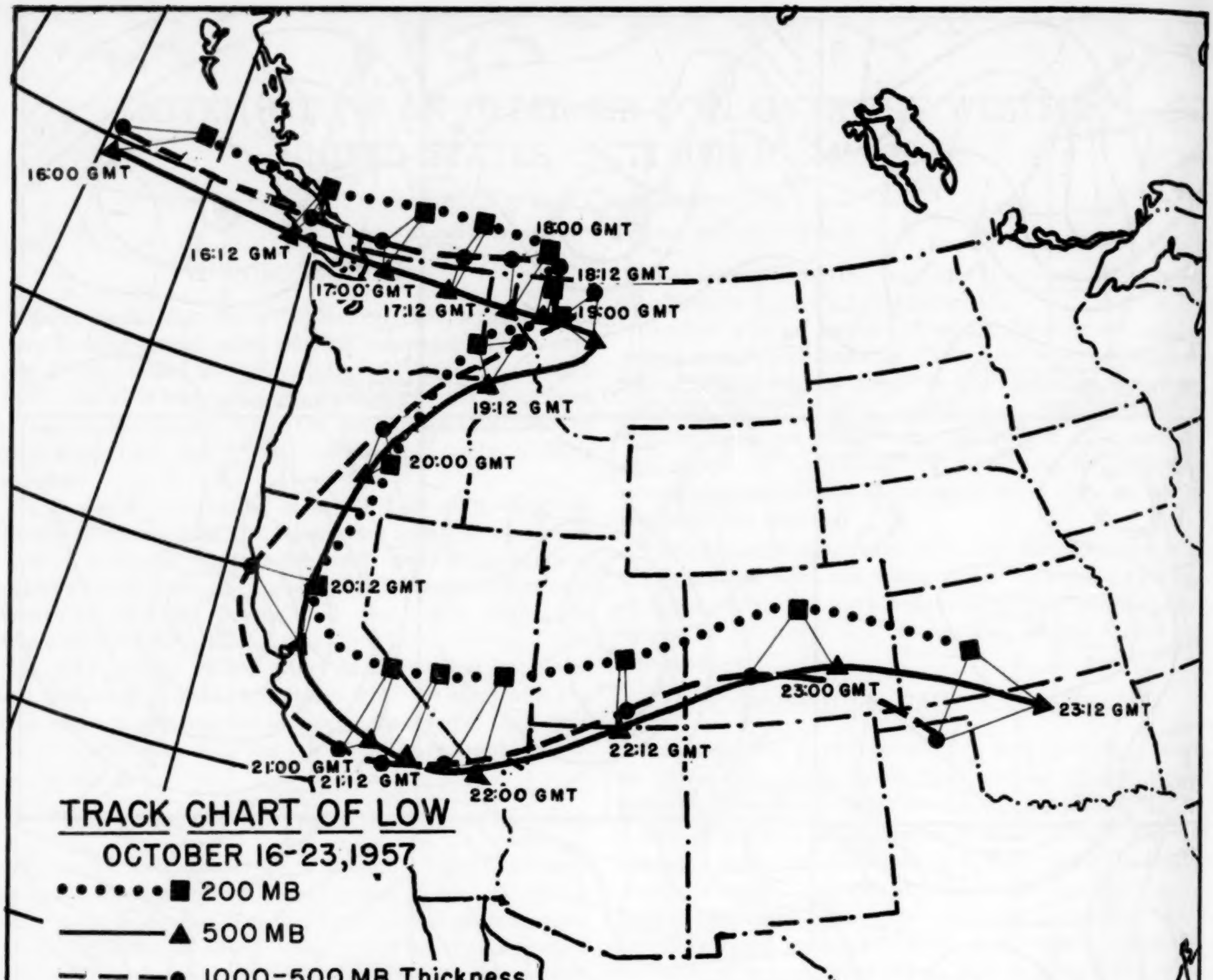


FIGURE 2.—Track of Low at 500 mb. and 200 mb. and of 1000-500-mb. thickness cold core, 1200 GMT, October 16 to 1200 GMT, October 23, 1957.

maximum for several different pressure surfaces (primarily 300, 250, and 200 mb.) are presented in relation to the center of the Low with respect to time. This shows that the strongest flow was about 70 knots in the southwestern quadrant the first day shifting slowly to the southeastern quadrant and dying rather abruptly the third day. During the middle of this period or about the beginning of the second day another maximum began to appear in the northwestern quadrant. Except for a temporary leveling off on the 20th, it gradually intensified and moved around the center to the southeastern quadrant where on the fifth day it reached a peak speed of approximately 150 knots. Figure 4, which gives the direction and speed of movement of the Low, is drawn to the same time scale as figure 3 so as to show the relationship that existed between the motions of the Low and the jet maximum. Of seemingly considerable import is the sharp change in direction of the Low on the 19th when the older maximum dissipated and the new peak to the northwest rapidly built up. Of further interest is the gradual recurvature of the Low as the jet maximum moved around the center. Not satisfactorily explained, however, in figures 3 and 4 is the sudden deceleration of motion on the 21st and rapid acceleration again 12 to 24 hours later. This apparently occurred at a time when the jet speed was increasing at a maximum rate. Perhaps the leveling off of the jet speed on the 20th was related to the deceleration, with a time-lag involved. Still, if this was so, one might rather expect a definite dip in the curve.

Another aspect of the overall steering current, seemingly of more than ordinary importance, was that at

certain intervals the surface and lower-level flow pattern was opposed to the general circulation pattern above. This seems to have been most influential around the 18th, 19th, and 20th, just prior to and after the sudden change in direction of movement of the Low. This is shown quite well in figure 5 where the surface flow is northeasterly and increasing under the Low aloft. Actually the circulation at and near sea level had been weak and easterly beneath the Low or trough from the beginning of the series of charts, which seems to explain the slow deceleration toward the east. Late in the series the lower-level flow offers the only obvious explanation for an upper Low movement in a direction south of east.

It may be worthy of some mention also, as indicated by the relative positions of the Low (fig. 2), that nearly all the eastward movement at 500 mb. was in fair agreement with the 200-mb. flow above. It should be noted here that only during the eastward progression was there any appreciable tilt between the two levels. Furthermore, motion of the 200-mb. Low was in good agreement with the 150-mb. flow above it.

Finally to be considered are the components of movement produced by a changing thermal field. For most of this series the Low was termed "cold," which by the usual definition implies little or no advection at levels where it exists. There was, in fact, little advection observable from existing data, and what there was occurred near mid-period and mostly at the higher elevations causing deepening of the center at all levels below. If any appreciable warming or cooling was produced by radiation, vertical motion, or other physical processes, it was not readily discernible. Hence it may be concluded that the thermal factors influencing the Low were for the most part negligible.

All the foregoing discussion has been given in an attempt to point out the various features of the stream of air acting around, above, and below the Low at any particular height to explain why it moved as it did. One may well ask if some of the explanations given may not overlap or even be the cause of others. Certainly the tendency or change field is more in the nature of an effect and probably should be used only to corroborate the net effect of all the causes. At any rate, it has been possible in every case but one to show a flow pattern acting that could cause the Low to move as it did. This one exception is the deceleration around October 21. All explanations attempted here are somehow insufficient.

4. APPLICATION OF PREDICTION METHODS

Next comes the problem of forecasting movement of the Low. Of course the more erratic the path the more difficult the prediction. Nice uniform motions or even regular accelerations and curvature for short periods present no great difficulty. It is the longer-range problem with irregularly moving systems that taxes the meteorologist's capabilities. The low pressure system under study was such a trying case.

For the remainder of this section the discussion will

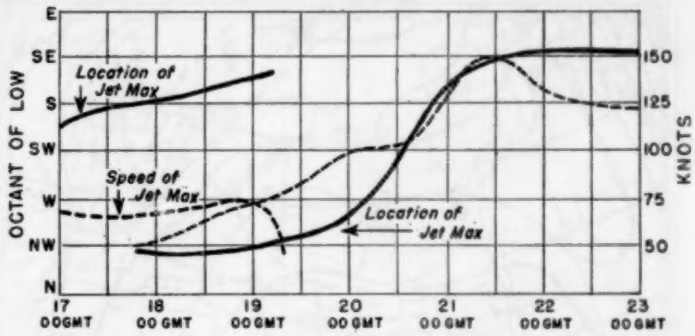


FIGURE 3.—Graph showing location and speed of jet maximum associated with Low, October 17–23, 1957.

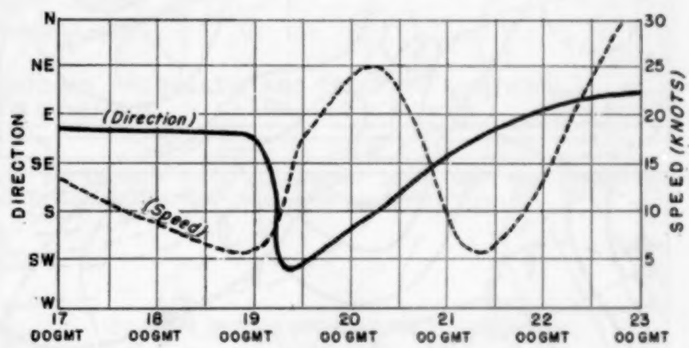


FIGURE 4.—Graph indicating mean speed and direction toward which Low is moving at 500 mb., October 17–23, 1957.

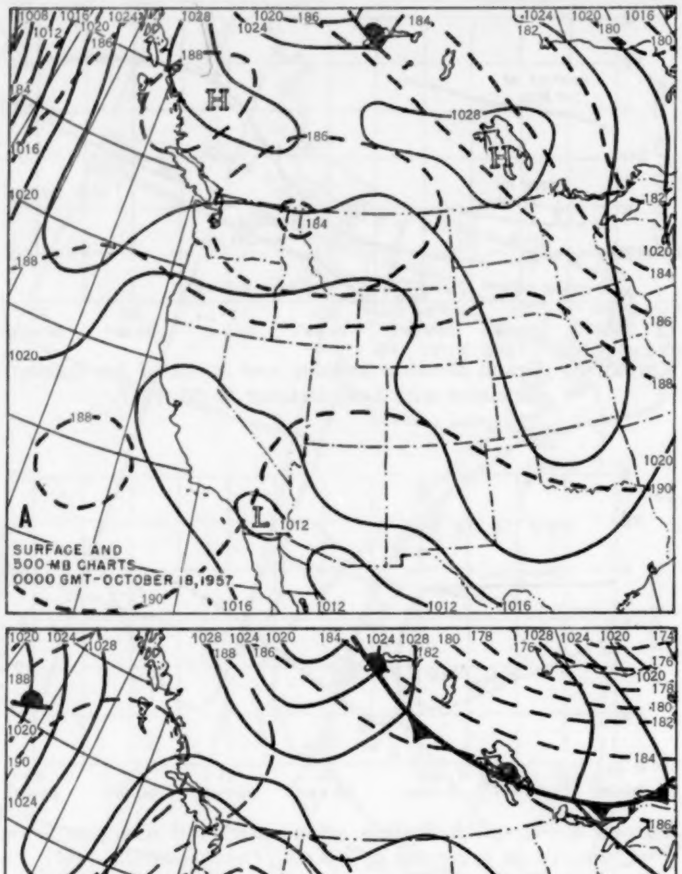
deal with a prognostic period of 36 hours unless otherwise stated.

In the two charts of figure 6 is shown a comparison between the observed positions of the Low and the positions forecast by two offices, the National Weather Analysis Center (NAWAC) and the Joint Numerical Weather Prediction Unit (JNWP). As is quickly perceived, neither did well, nor did one prove to be noticeably better than the other in this case. The question arises then whether any of the known objective or subjective techniques would have verified better. Several of these, to the extent time has allowed, have been tested and will be discussed individually as to their value in this particularly difficult case.

First, the process of pure extrapolation proved superior to any other at certain select times but as a whole was very unsatisfactory. Extrapolation could not take account of the numerous reversals of trend shown in the track.

Advection of vorticity in a barotropic field using the Fjørtoft [2] graphical technique was studied briefly. It was abandoned, however, because it was felt the JNWP method incorporates refinements of the same process and would show better the merit of this approach.

As will be seen in figure 6 the JNWP technique moved the Low in a very general path comparable to that of the observed but was consistently too slow, often by a considerable margin. In evaluating this system in the given situation it must be pointed out that because the whole series was largely barotropic in nature methods



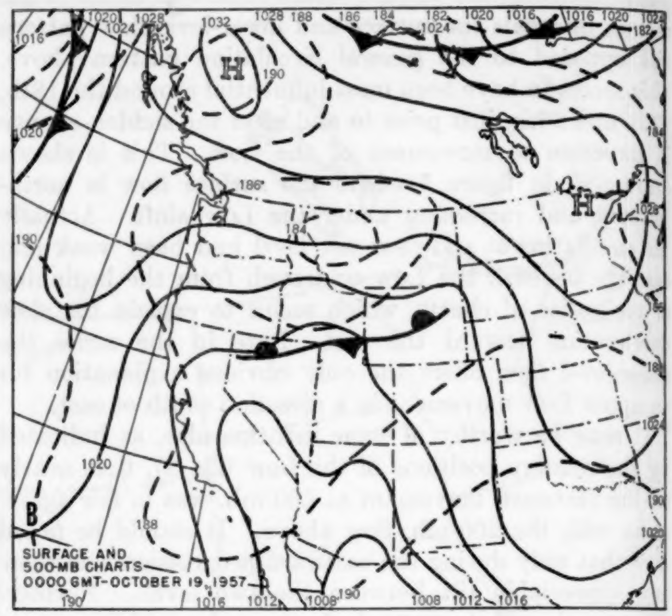


FIGURE 5.—Surface isobars and corresponding 500-mb. contours for 24-hour intervals, October 18–20, 1957, showing relationship of movement aloft to surface flow pattern.

based on barotropic models would have been expected to operate at their near best.

Calculations were made using the Wilson Grid Method [3] for each map of the series. The results were quite good during the first part of the series when the Low was moving eastward but when the sharp shift toward the southwest occurred the computation failed for three consecutive maps. When the change was finally detected, the computed position lagged the actual position by a significant amount and continued thus throughout the remainder of the series. The overall results of this method were certainly no worse than those previously discussed and might well be considered superior in the early part of the series. In utilizing this procedure it often seems advisable to cut down the number of grid units in all directions by a certain percentage so as not to overlap into another pressure or contour system. In the computations made here the full grid was used.

An attempt was made to use the Petterssen equation [4] for calculation of wave speeds; however, it does not lend itself well to reckoning the movement of centers. If one makes the assumption that the center will remain the same distance from the core of the jet stream along the trough (or ridge), then a fair computation on the center may be made. This formula is difficult to apply in several other respects in that it requires, first, a well-defined trough (or ridge) line which lies in a region of plentiful and reliable data not only to give an accurate analysis but also to determine the wind speed in the trough (or ridge). In addition to this it makes no allowance for amplitude of the wave. Of the computations made using this method all projected the system too far ahead and often in a direction at considerable odds to the observed. This latter effect is due in part, at least, to failure of the system to allow for rotation of the trough (or ridge) around either an imaginary or actual center. This limits its use in the calculation of many short-wave movements to very short periods of time. As it was applied to this specific case the choice of values and locations of the trough was so uncertain as to make highly questionable the results obtained. The question arises whether this method should be applied to systems such as this.

Examination was made of the Scherhag Theory [5] that steering of what Scherhag terms "cold air drops" (cold Lows aloft with no closed circulation at the surface) is controlled by the surface and lower-level flow. Scherhag states that the movement will be deflected across the iso-

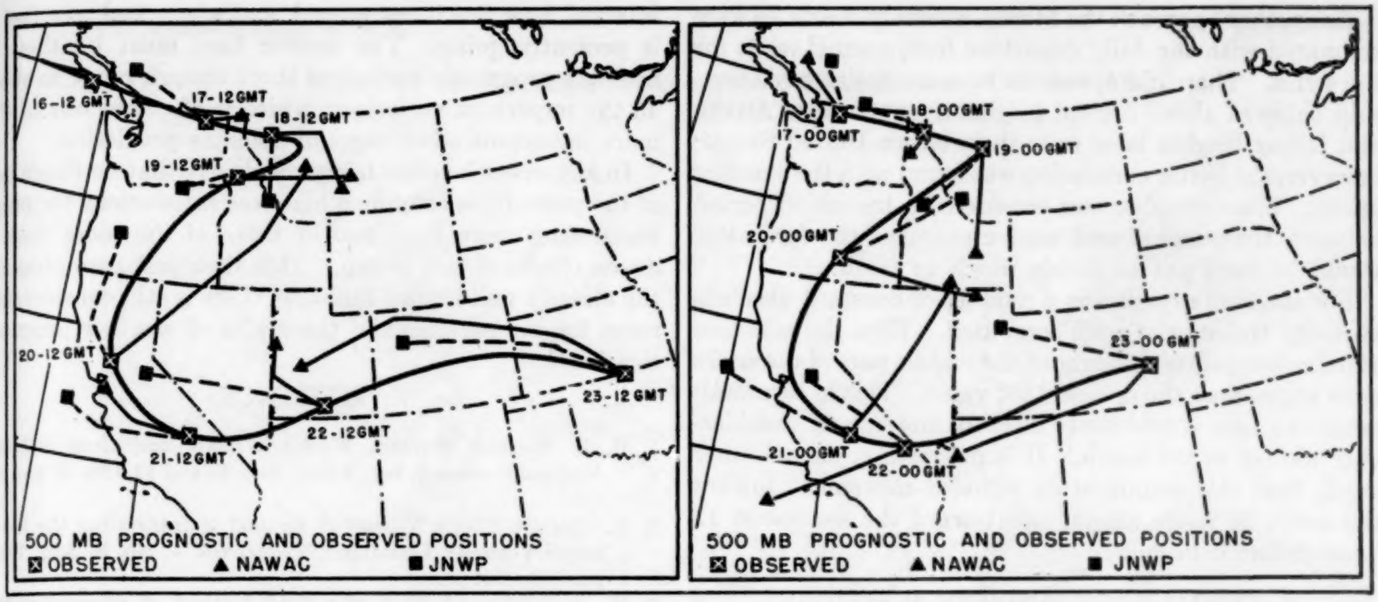


FIGURE 6.—36-hour 500-mb. prognostic positions of low center—NAWAC (triangles) and JNWP (squares)—with connecting lines showing corresponding observed positions. (1200 GMT, October 16–23 left, and 0000 GMT, October 17–23, right.)

bars toward lower pressure and at a speed somewhat less than the gradient wind indicated by the sea level isobars. He does not, however, assign any quantitative values. In applying his theory to this study, 80 percent of the gradient wind speed and a 20° deflection across the isobars were chosen. The system has a very limited application and could be used in only a part of this sequence. The results obtained, however, were the best and about the only calculations that indicated motion of the Low toward the southwest during the early part of the series before and at the time the Low actually started to move in that direction. This, of course, began too soon because some easterly flow was indicated under the Low from its inception. However, one must realize there existed an influence tending to move the Low eastward which had first to be overcome before it could be moved with the current below. The effects of the east-west flow at the surface were very evident in the deceleration pattern from the 16th to the 19th, and in the acceleration afterward. It appears from this very limited application of Scherhag's theory that better results might be obtained by using a deflection angle of approximately 40° across the existing surface isobars or else prognosticating the surface flow pattern at 12-hour intervals and then moving the upper Low with the mean current.

Bjerknes' eccentricity formula [6] gave results as variable as the Low movement itself but not generally in phase with it. Here again proper selection of pattern, orientation of trough line, and accurate wind speeds are all-important. A still further limitation is the latitudinal five-degree radius of curvature found by O'Connor [7] to be the only radius yielding good results. It would appear from experience in this case that the eccentricity formula should be applied only when there is no doubt of a proper fit and reliable data.

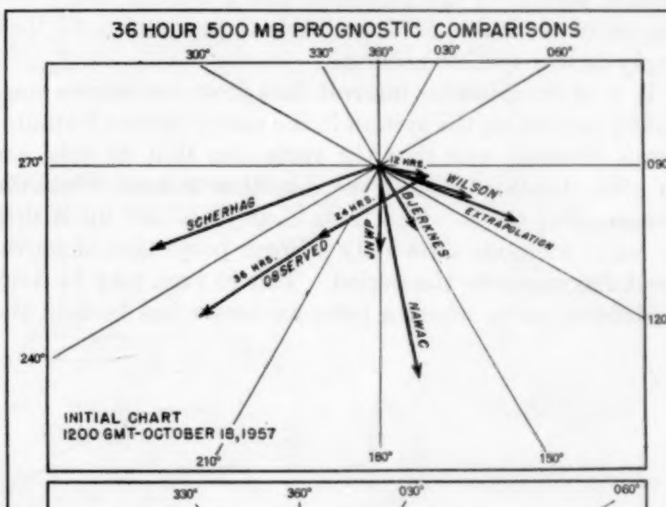


FIGURE 7.—Hodographic form of 36-hour 500-mb. prognostic comparison showing a variety of movement computations with 12-hour vectors of observed movement at two critical periods of the series.

As another approach the Martin anomaly charts [8] were compared with the daily departure from normal maps for the series. There did appear to be some positive relationship between above normal heights over southern Alaska and falling heights later over the western United States; however, the better correlation was found with the summer group. Since October was considered a transition period between the summer and winter averages the forecaster would be hard put to decide which to favor.

For the final experiment a number of constant absolute vorticity trajectories were computed. Here the selection of inflection points throughout the middle part of the series gave angles near the critical 130° value. This in turn indicated the Low would move offshore and cut off considerably too far to the south. It is interesting, on the other hand, that this computation signaled movement toward the south 24 hours ahead, and toward the southwest 12 hours before it began.

5. SUMMARY OF PREDICTION RESULTS

Figure 7 presents two hodographic forms of comparison for some of the techniques discussed in the foregoing paragraphs. These comparisons are made for two of the most critical periods of the sequence, and represent fairly well the relative values of these various procedures as they apply in this specific problem.

It is of considerable interest that most procedures start out by projecting the system in the nearly correct instantaneous direction and that the variations that do exist are so often tending toward the direction toward which the system later turns. One fault clearly pointed up is that so many methods show only a linear projection of movement for whatever the period. This in turn may be very misleading as to where a pressure center has been in the interval, how fast it has moved, and where and how fast it is presently going. The answer here must be then in multiple prognostic periods of short enough range to show all the important variations, which is of course one of the more important advantages of machine prediction.

In any event it seems fairly conclusive that no single one of the procedures examined here was satisfactory for prognosticating more than two or three of the more than a dozen charts of this group. This then just reemphasizes the already well known fact that there is still considerable room for improvement in the realm of weather prognostication.

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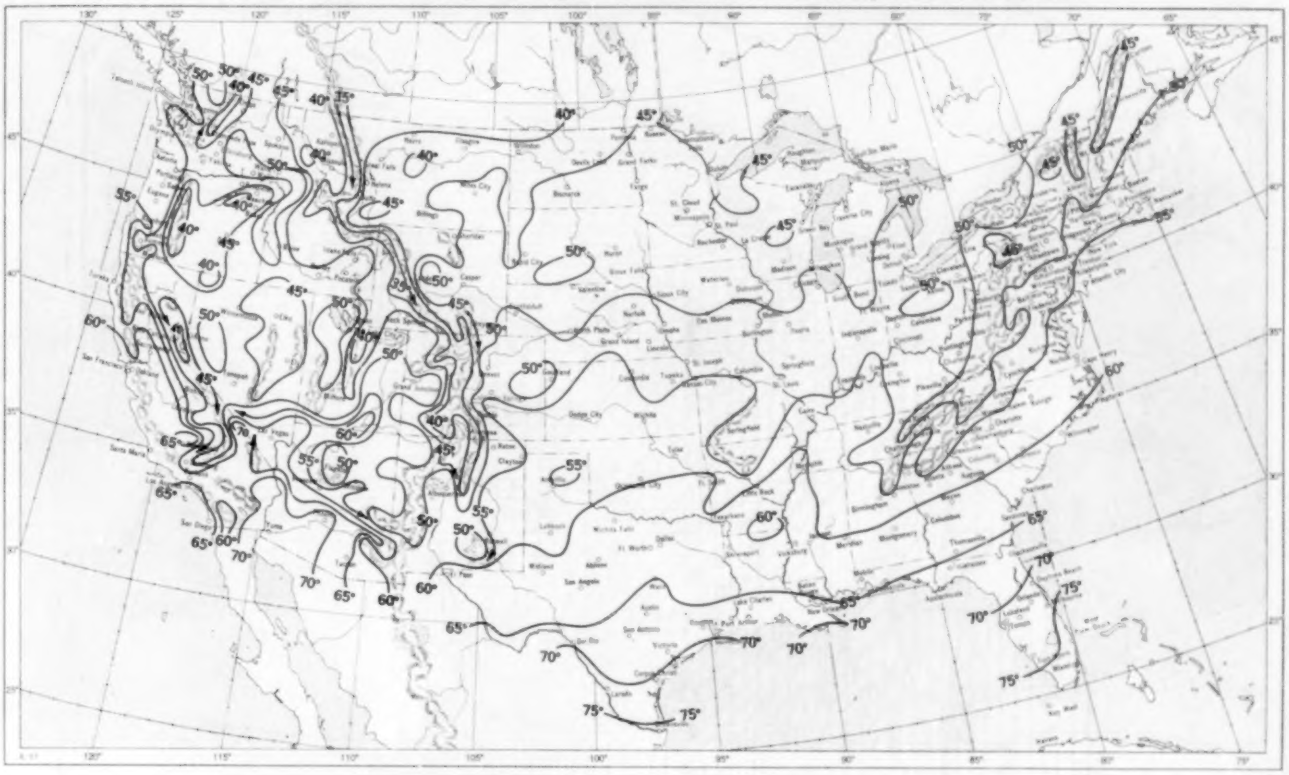
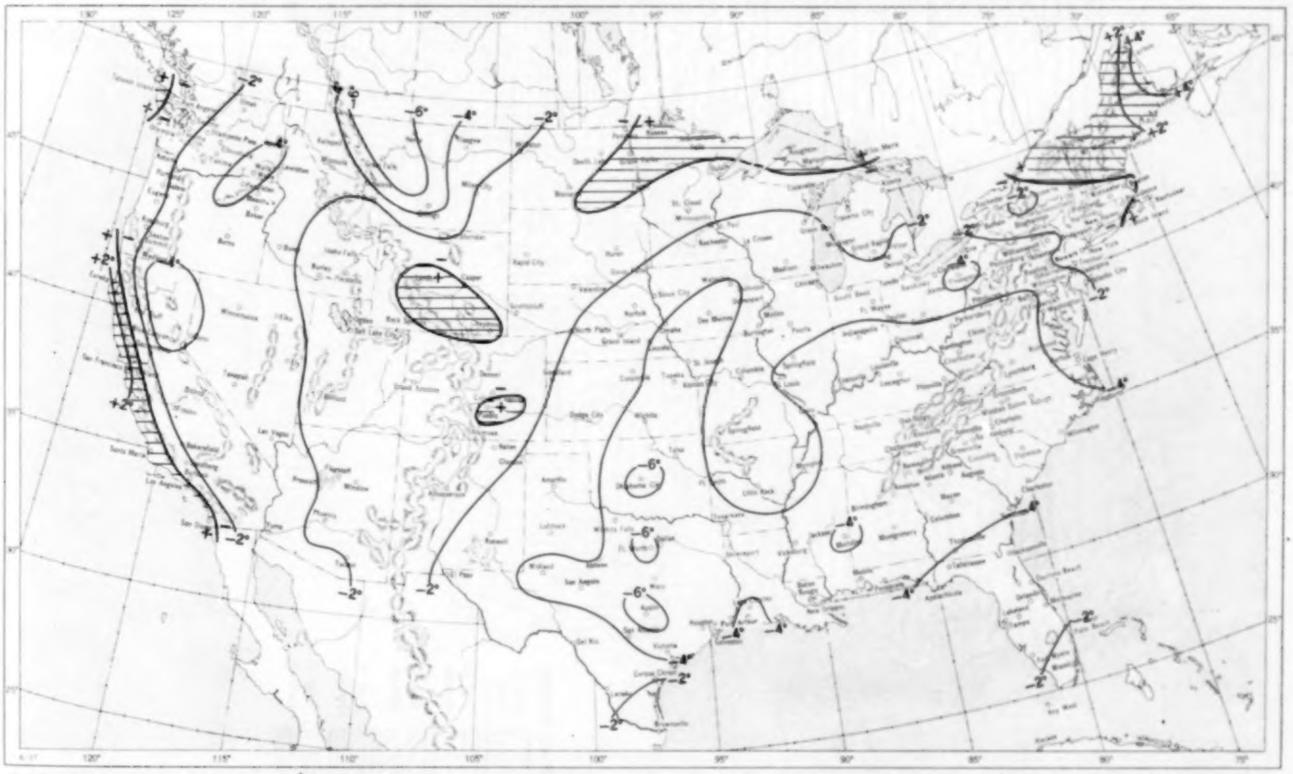
Chart I. A. Average Temperature (°F.) at Surface, October 1957.



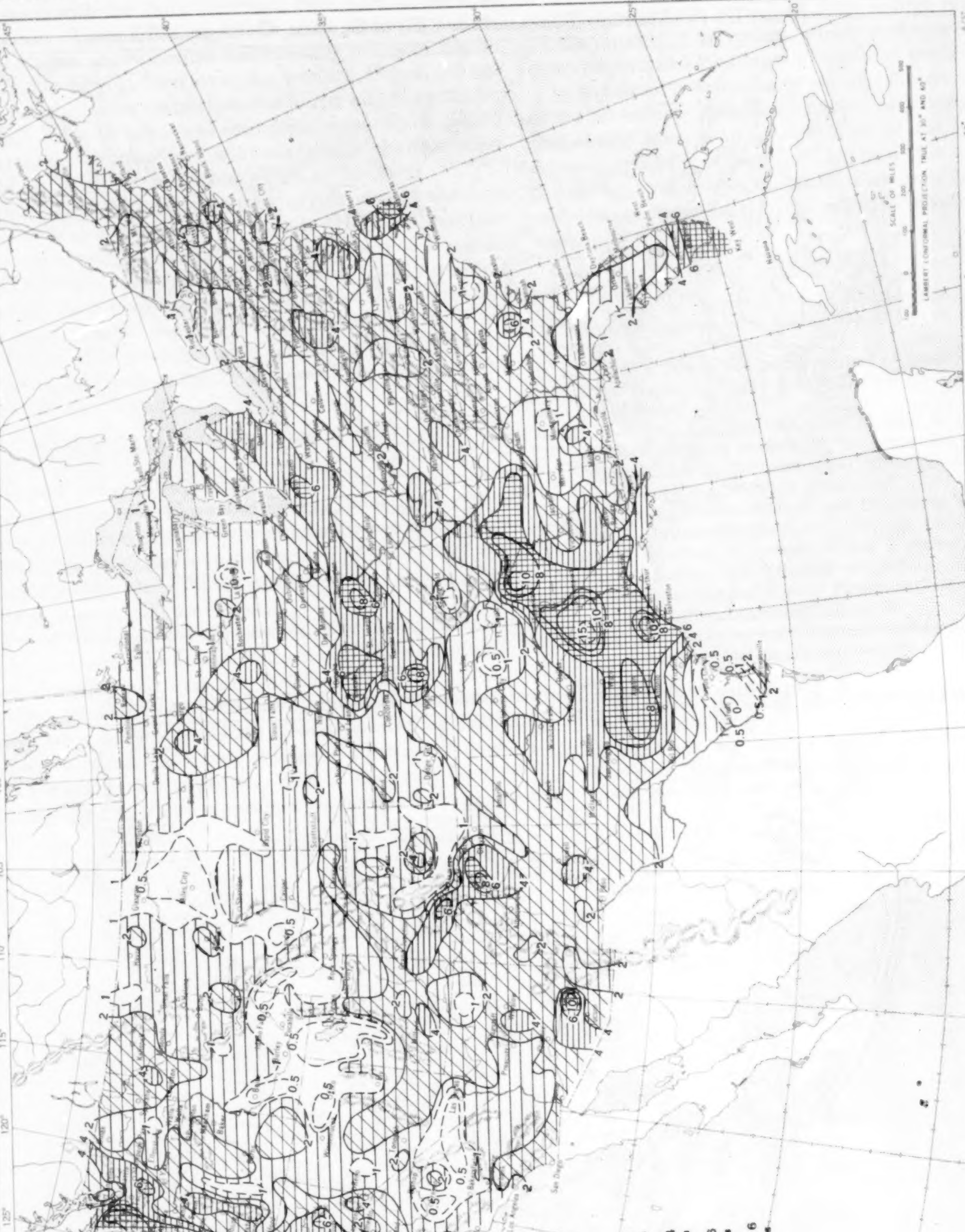
B. Departure of Average Temperature from Normal (°F.), October 1957.



A. Based on reports from over 900 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.

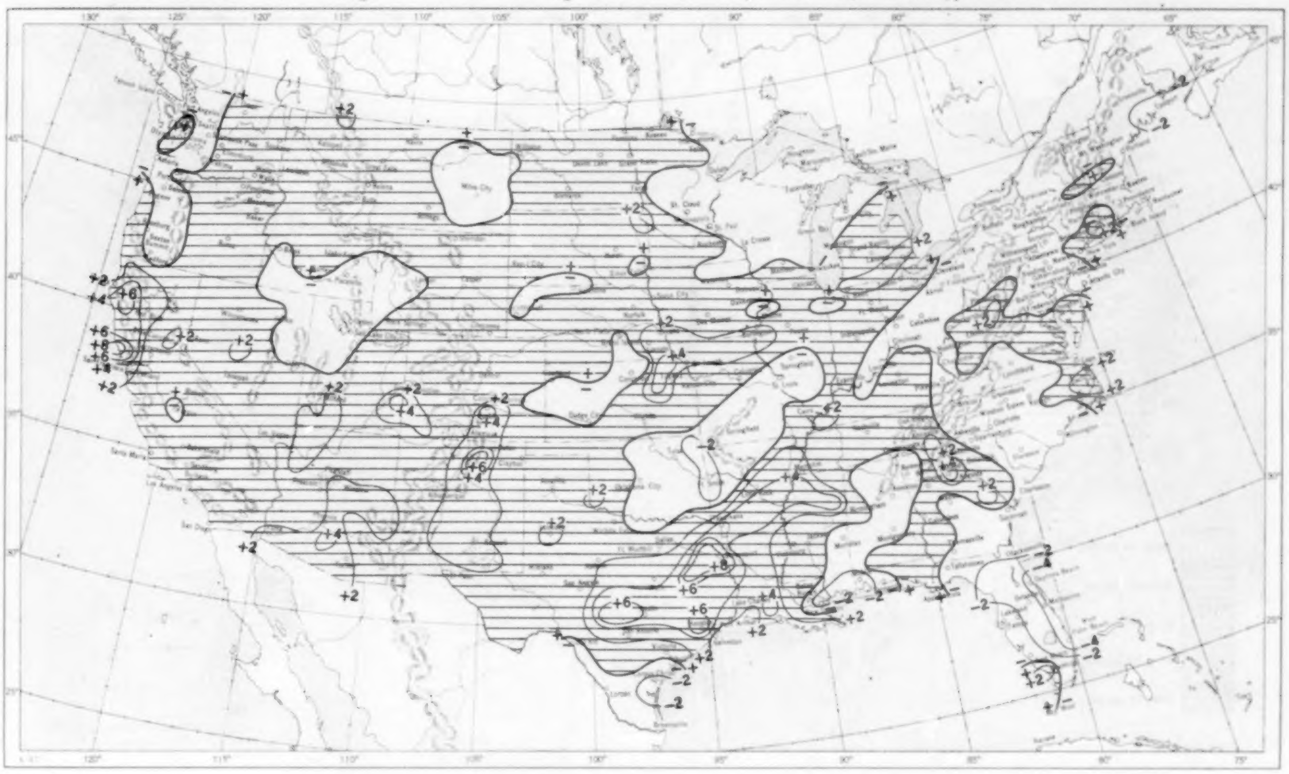
B. Departures from normal are based on the 30-yr. normals (1921-50) for Weather Bureau stations and on means of 25 years or more (mostly 1931-55) for cooperative stations.

Chart II. Total Precipitation (Inches), October 1957.

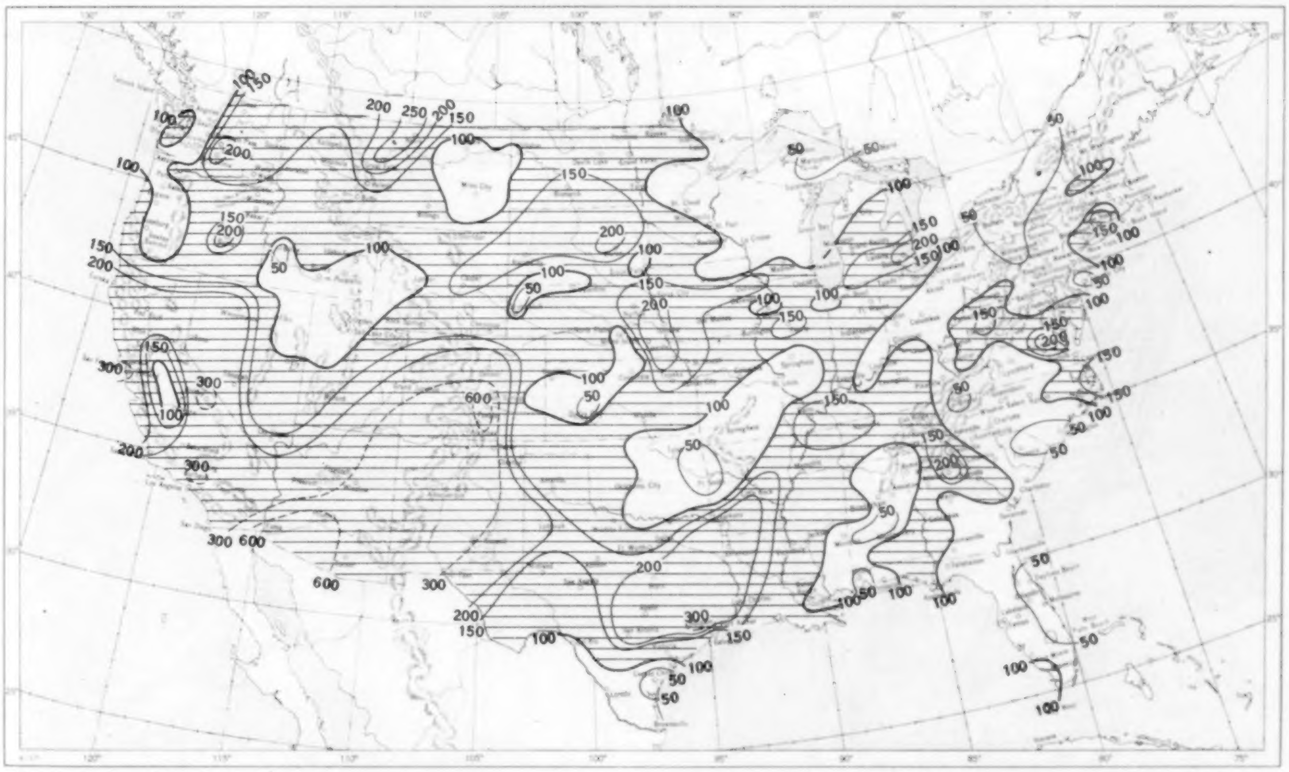


Based on daily precipitation records at about 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), October 1957.

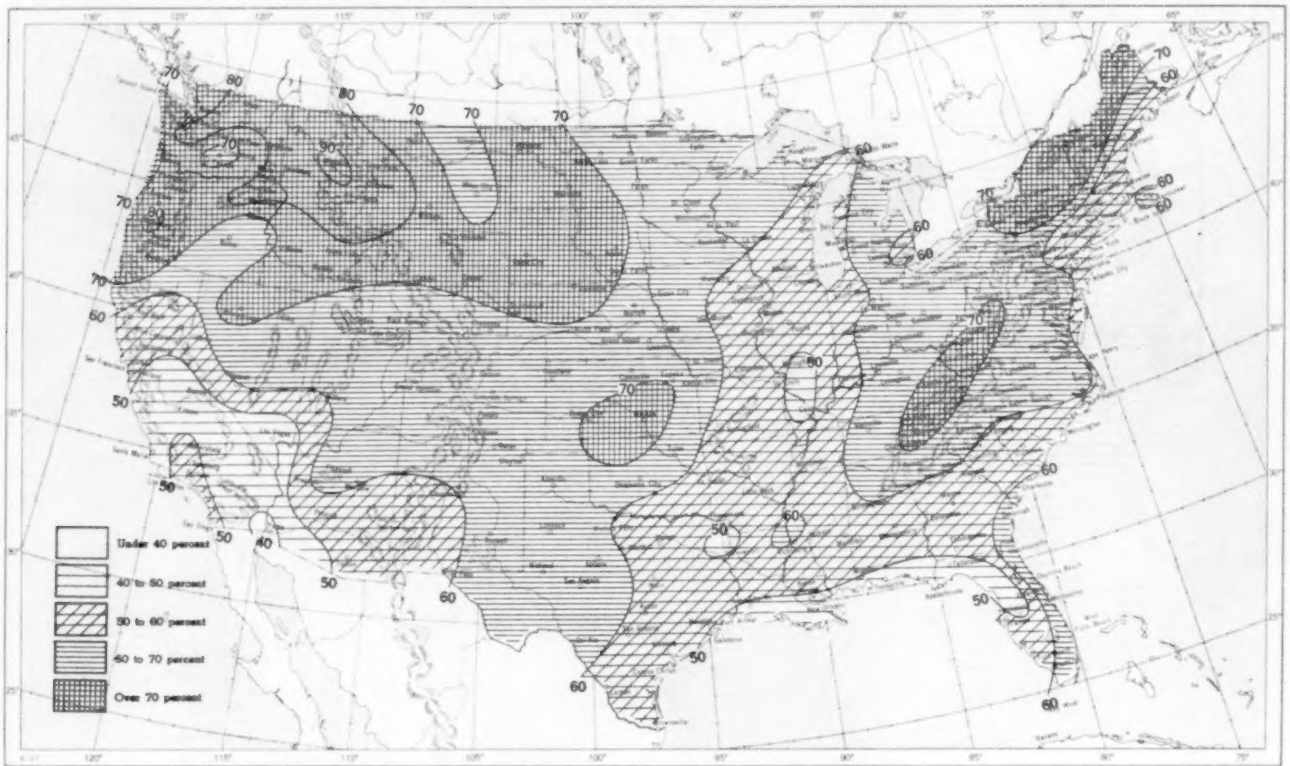


B. Percentage of Normal Precipitation, October 1957.

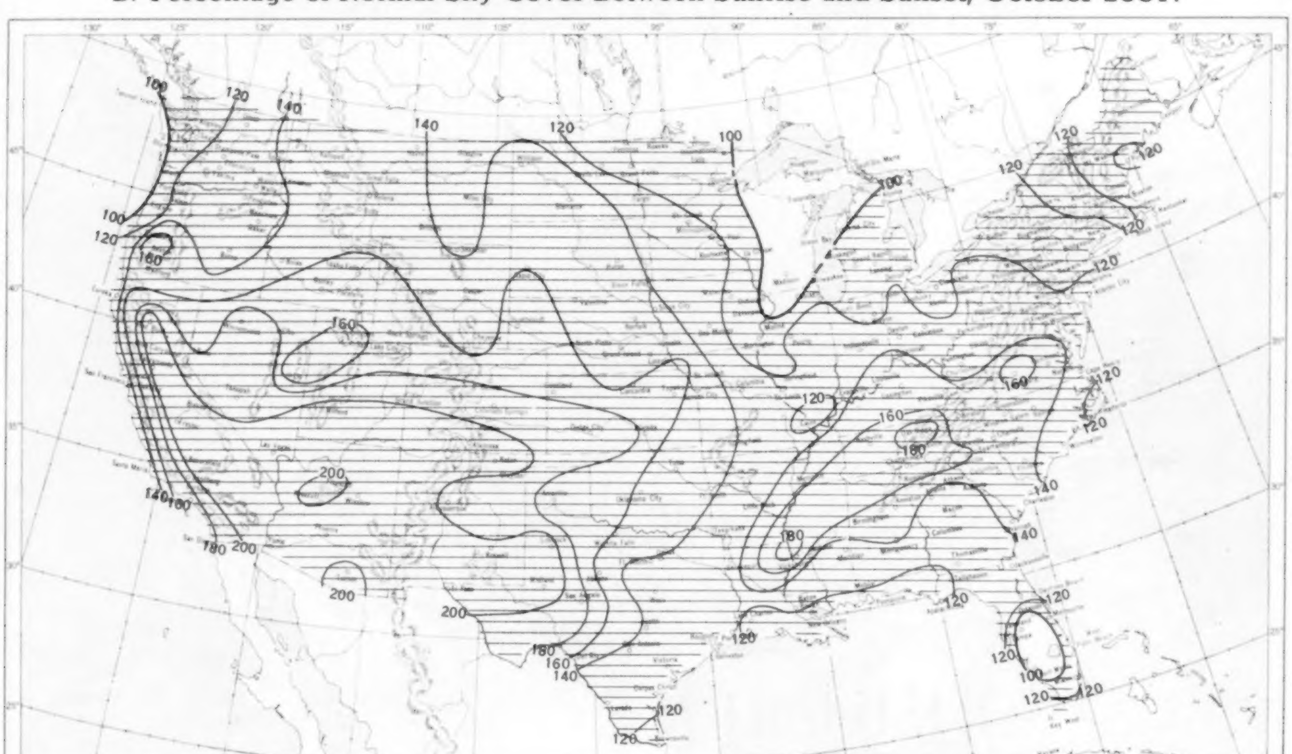


Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, October 1957.

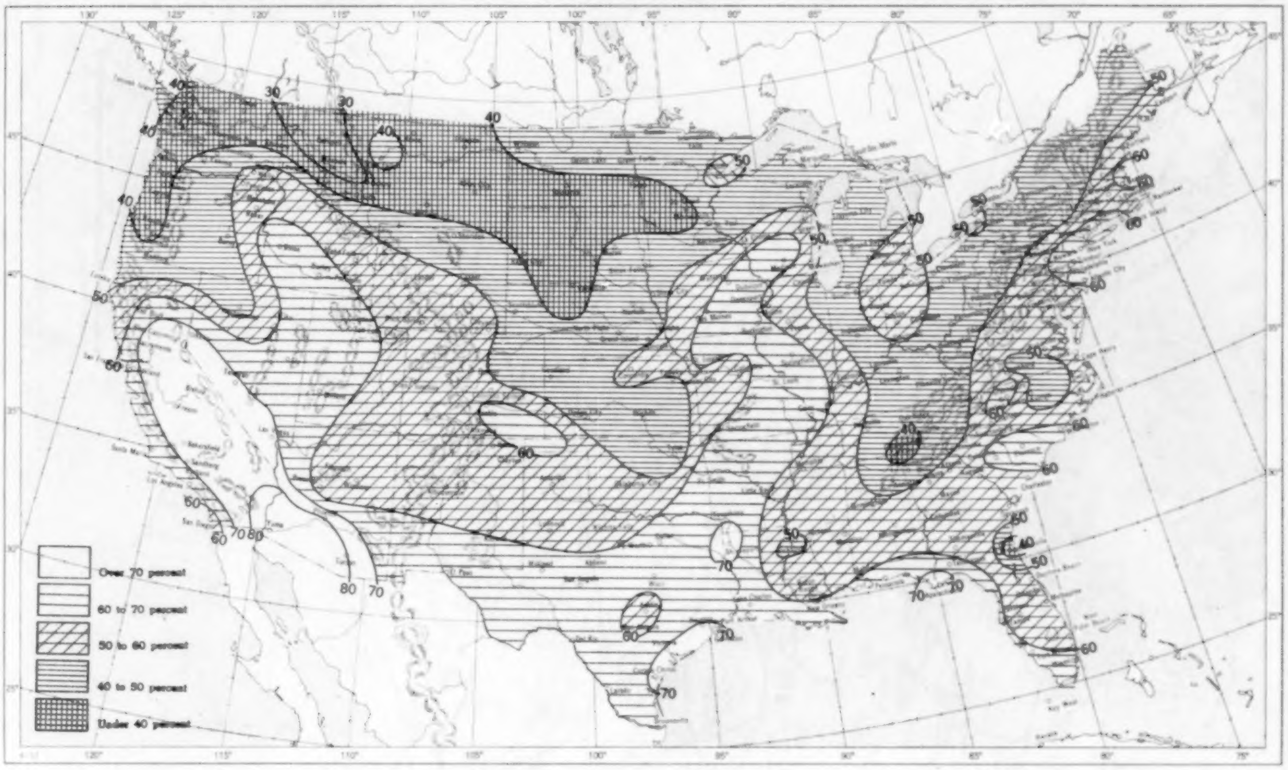


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, October 1957.

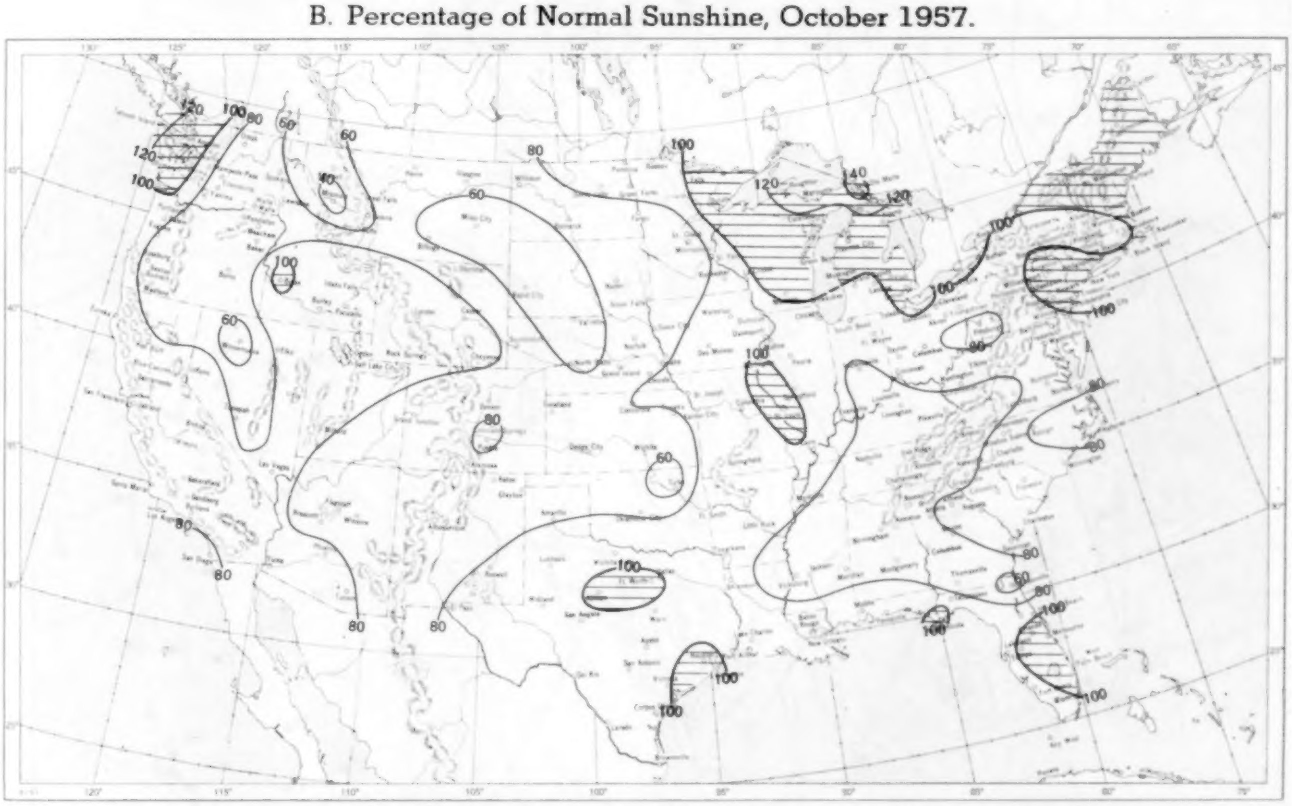


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, October 1957.



B. Percentage of Normal Sunshine, October 1957.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, October 1957. Inset: Percentage of Mean Daily Solar Radiation, October 1957. (Mean based on period 1951-55.)

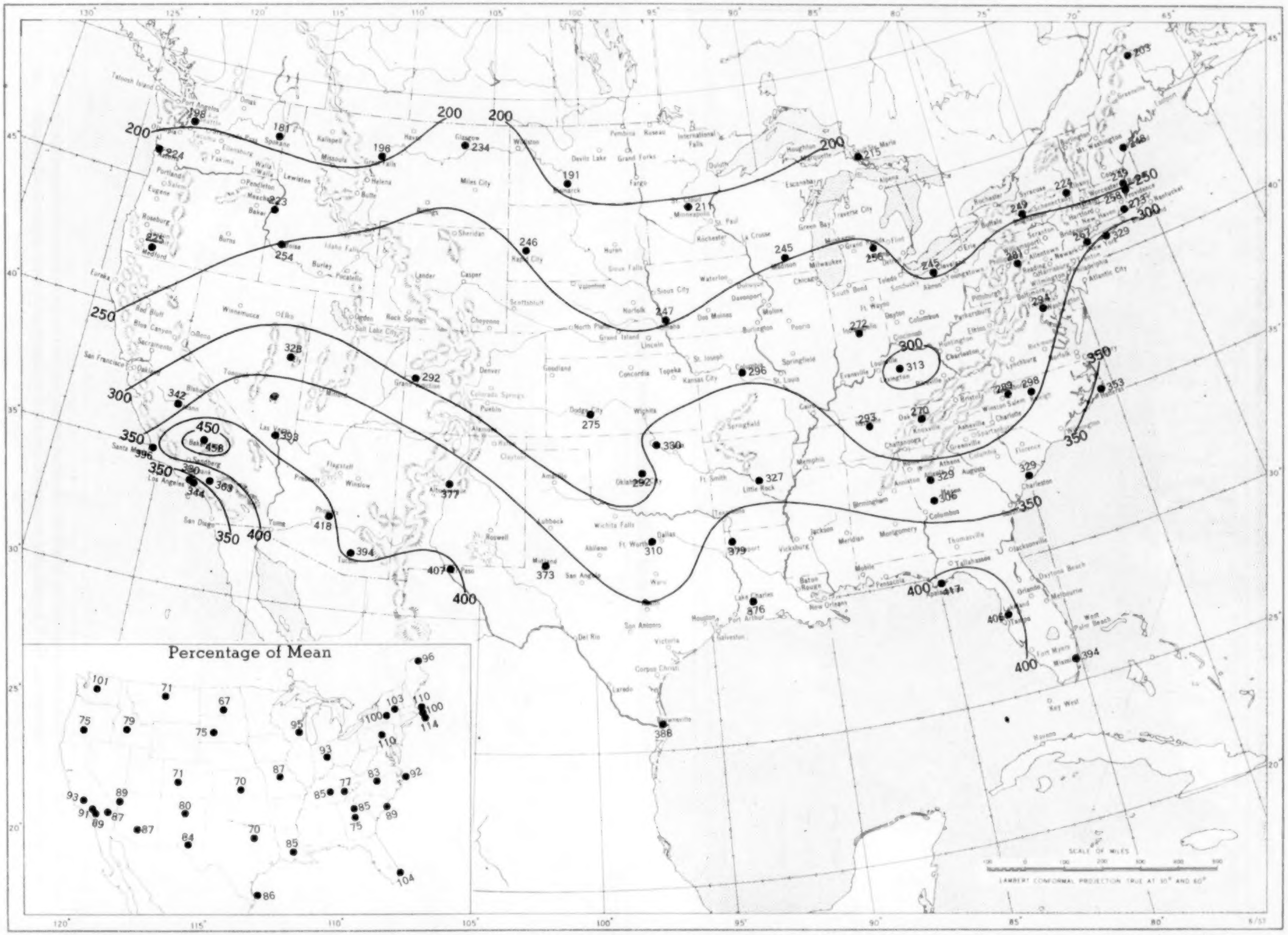
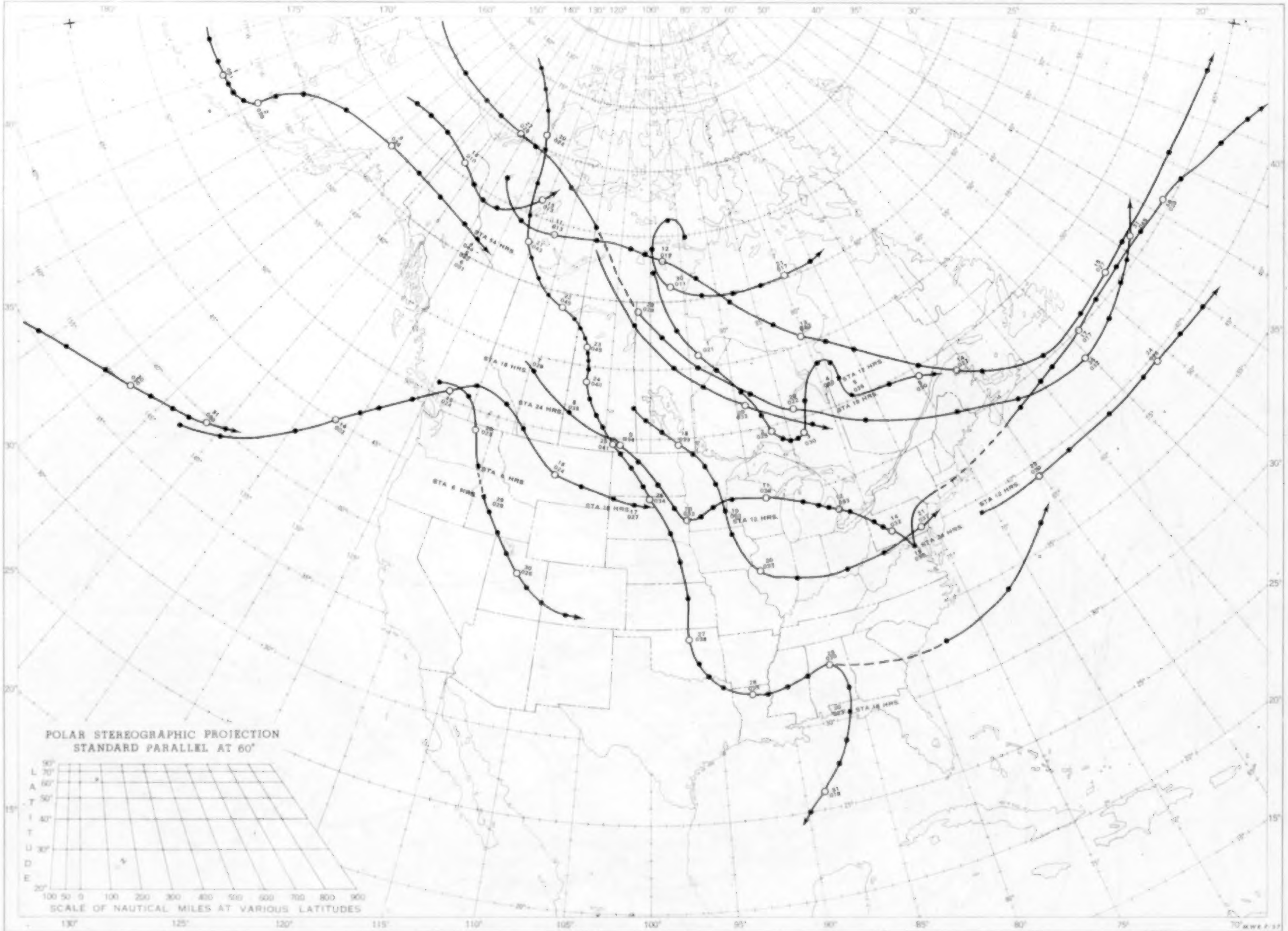


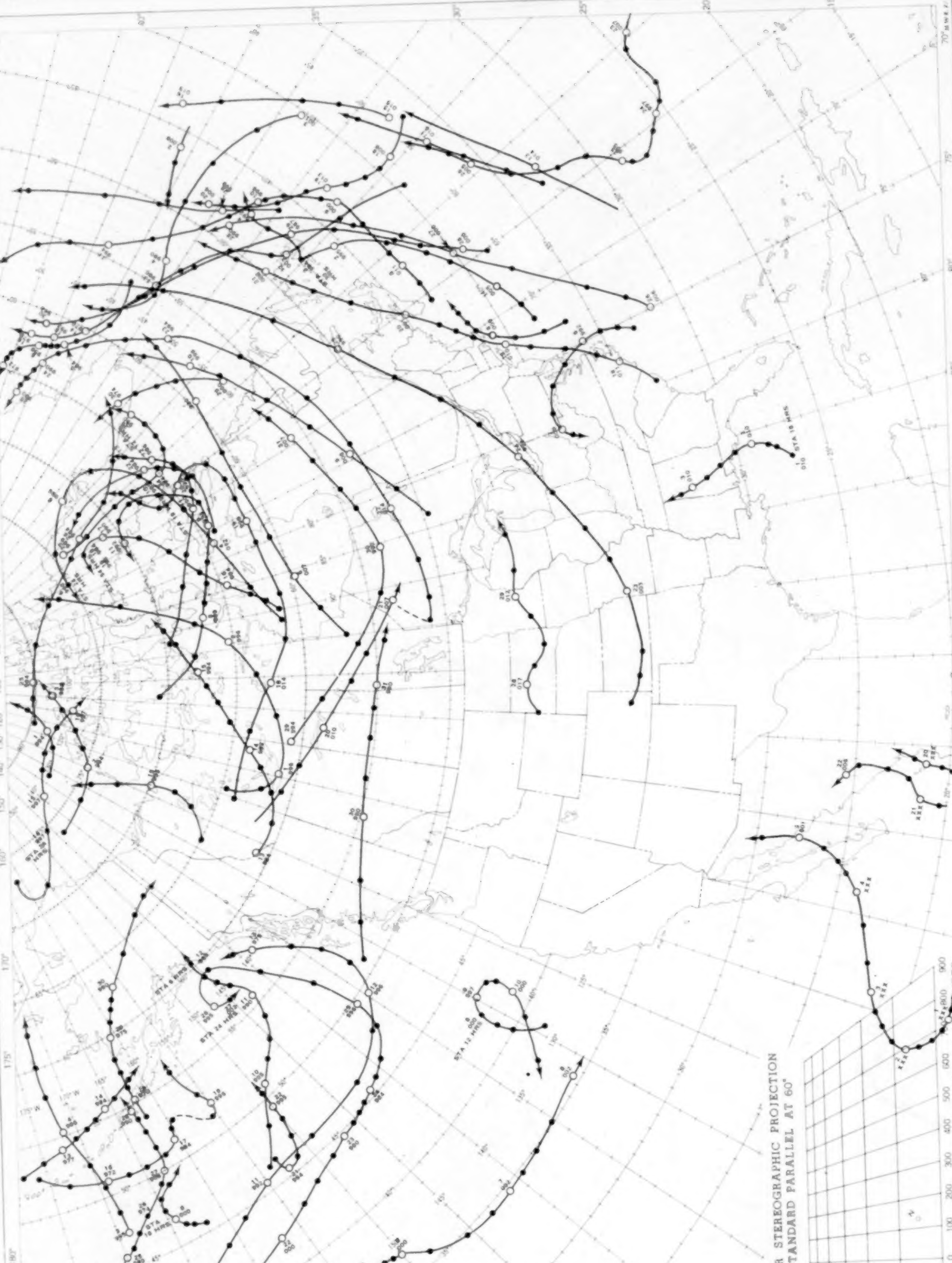
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm.$^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. The inset shows the percentage of the mean based on the period 1951-55.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, October 1957.



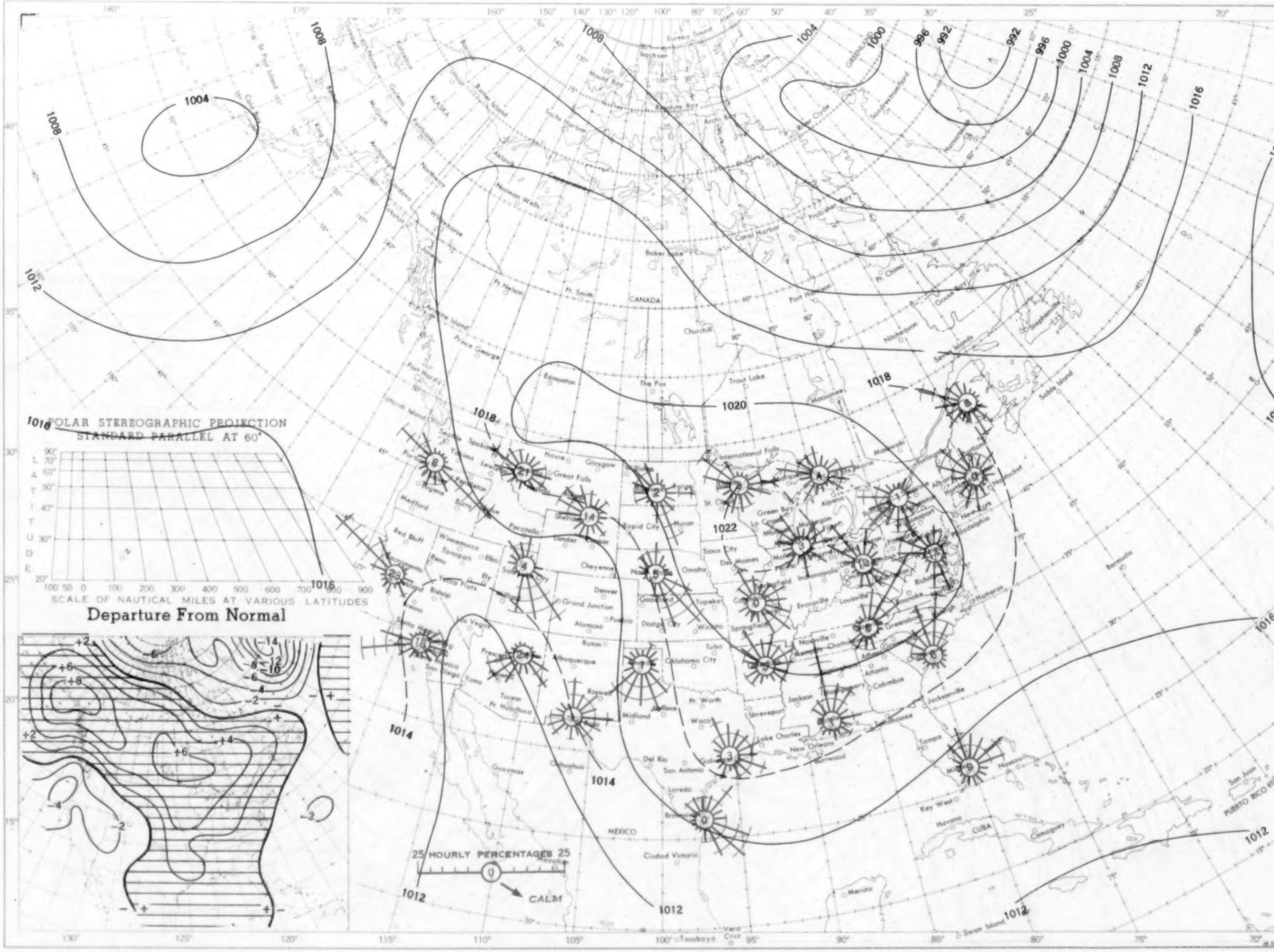
Circle indicates position of center at 7:00 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, October 1957.



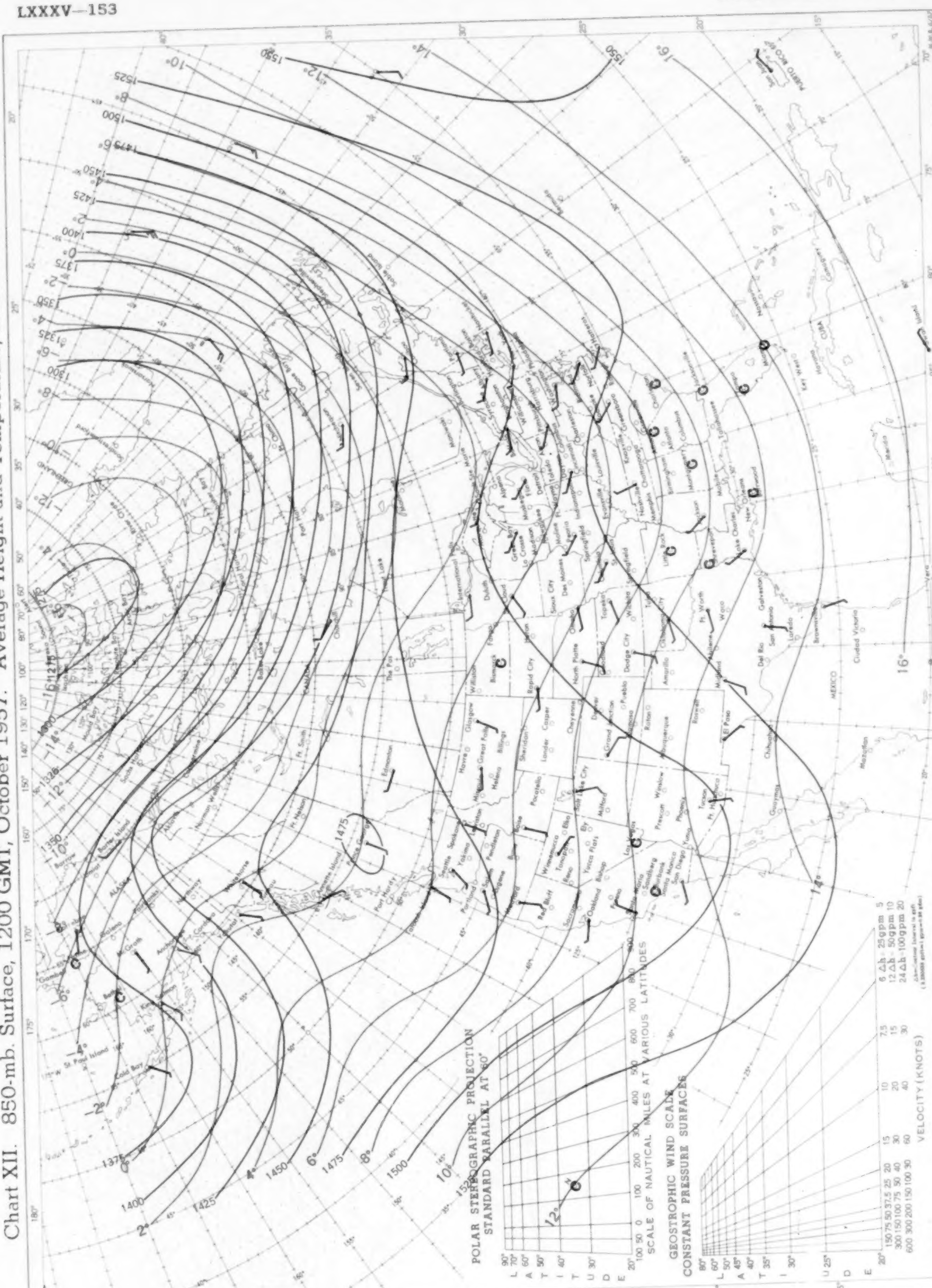
Circle indicates position of center at 7:00 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, October 1957. Inset: Departure of Average Pressure (mb.) from Normal, October 1957.



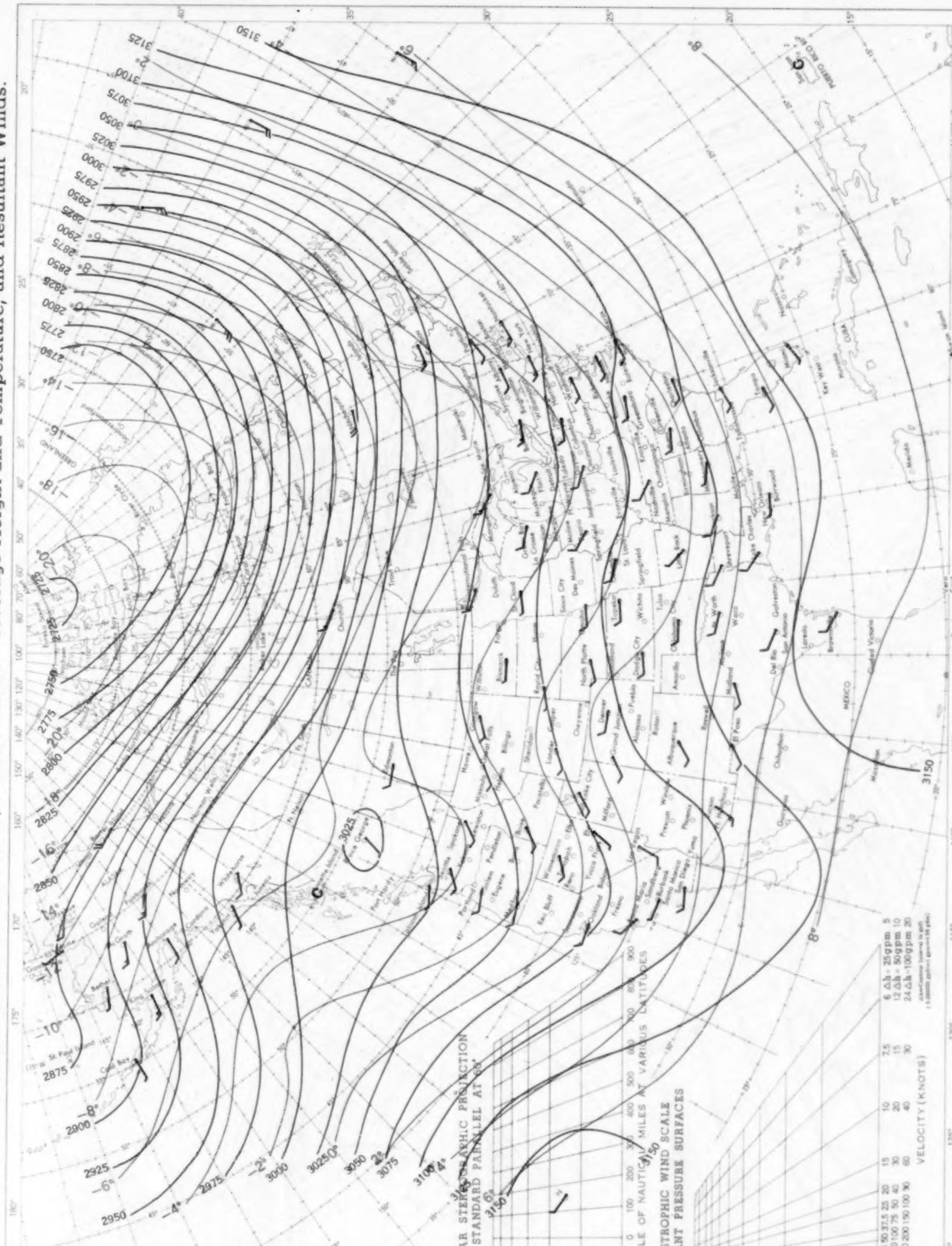
Average sea level pressures are obtained from the averages of the 7:00 a. m. and 7:00 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. 850-mb. Surface, 1200 GMT, October 1957. Average Height and Temperature, and Resultant Winds.



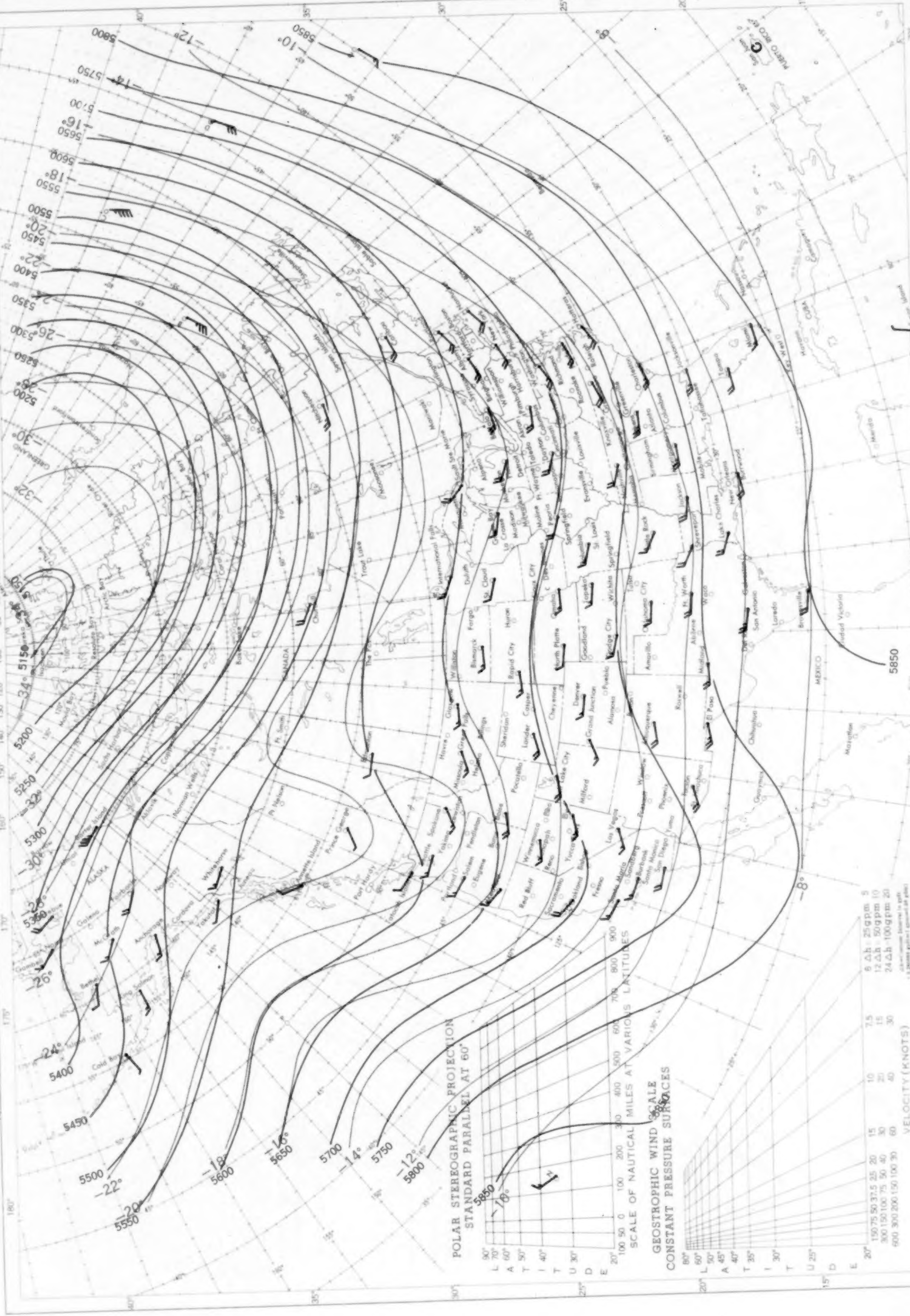
Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters). Temperature in °C. Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. All wind data are based on rawin observations.

Chart XIII. 700-mb. Surface, 1200 GMT, October 1957. Average Height and Temperature, and Resultant Winds.



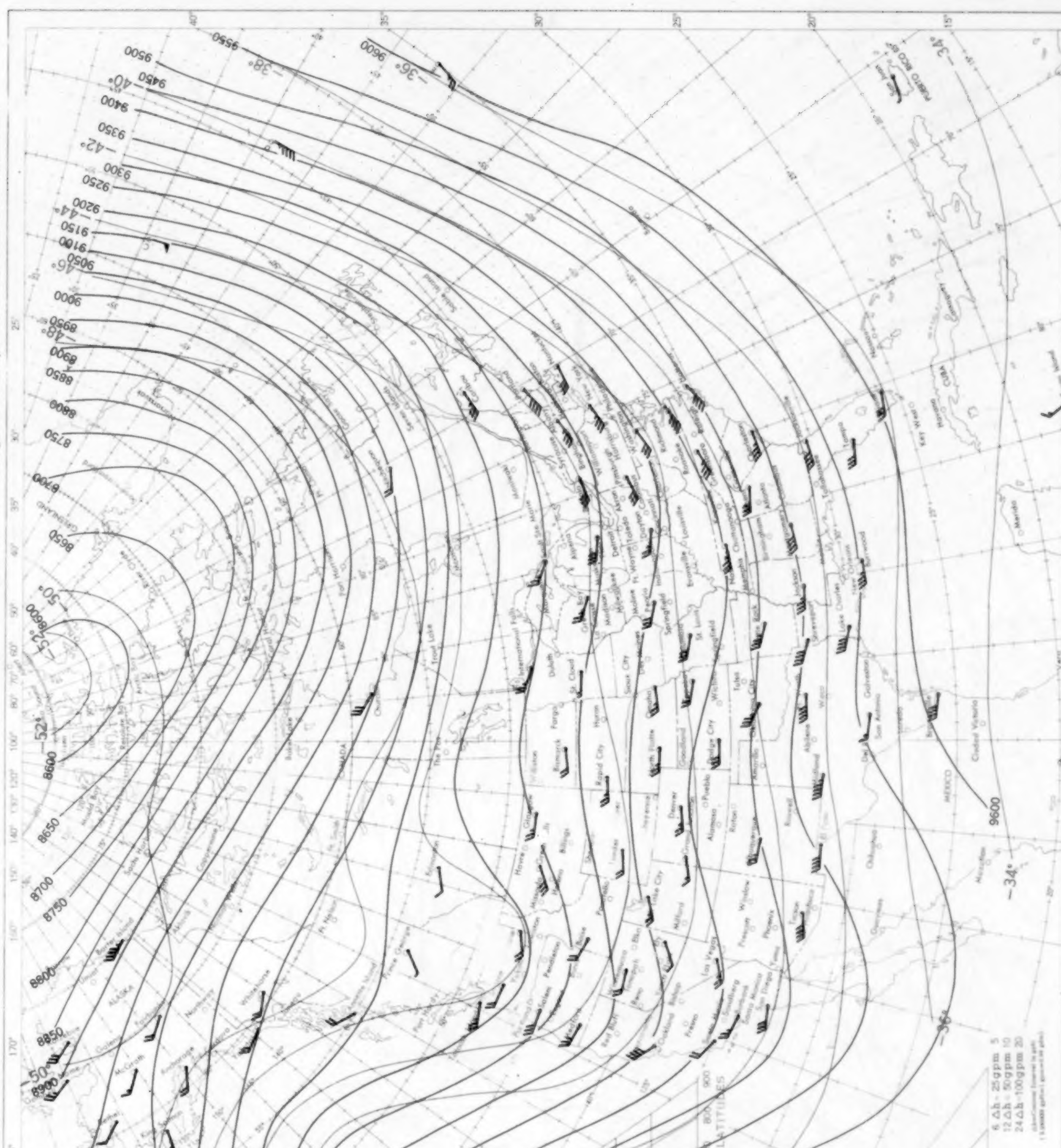
See Chart XII for explanation of map.

Chart XIV. 500-mb. Surface, 1200 GMT, October 1957. Average Height and Temperature, and Resultant Winds.



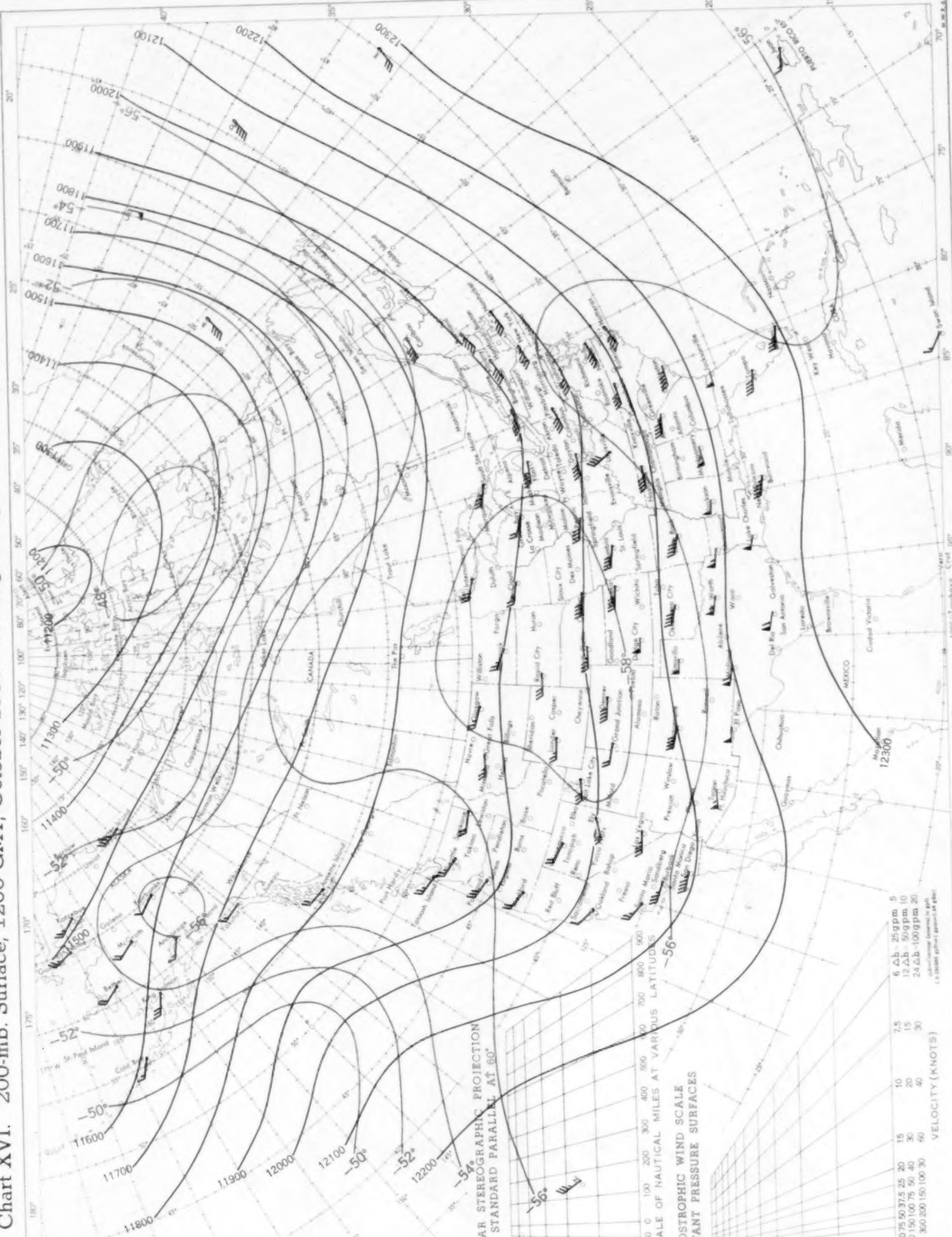
See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 1200 GMT, October 1957. Average Height and Temperature, and Resultant Winds.



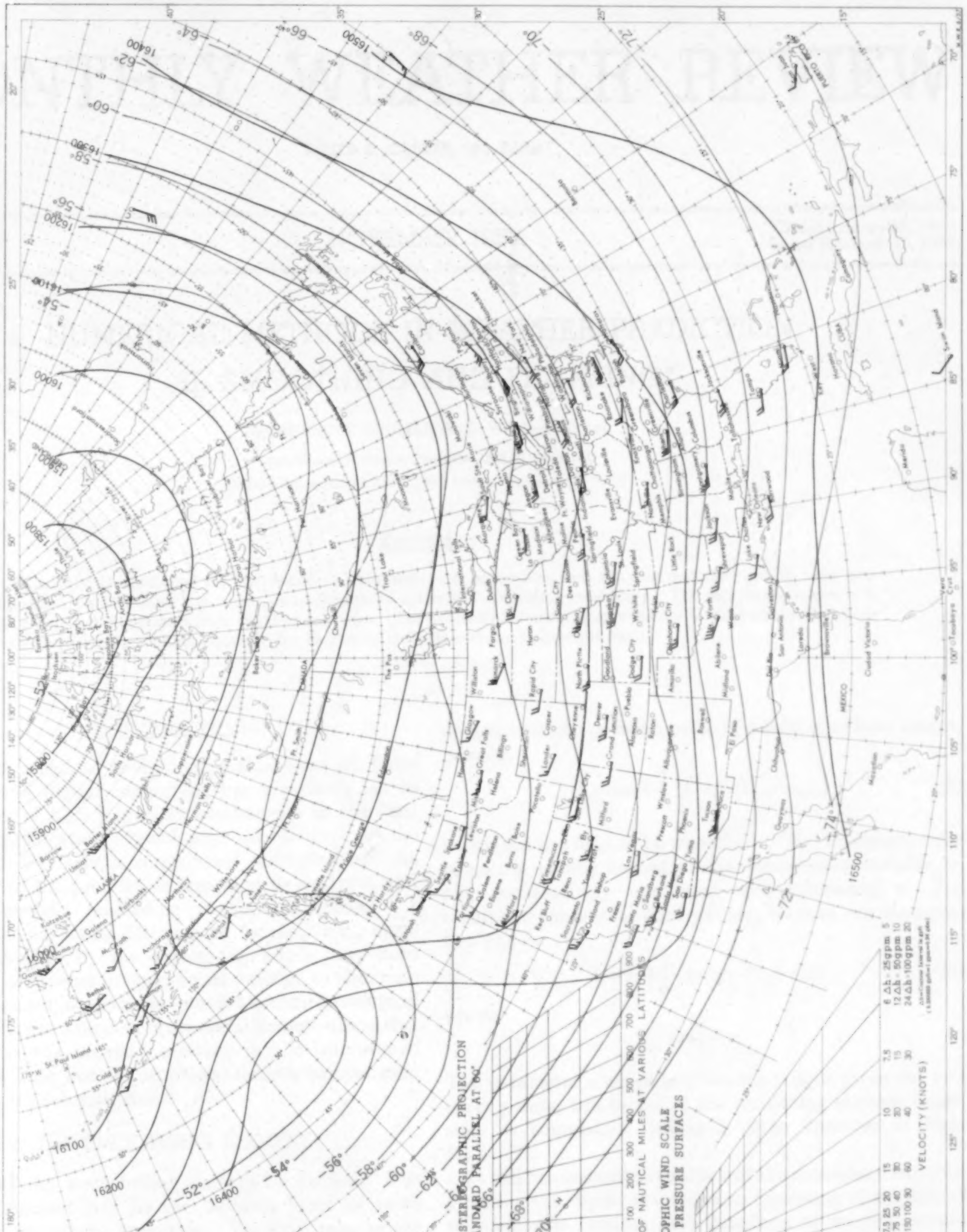
See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 1200 GMT, October 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.

Chart XVII. 100-mb. Surface, 1200 GMT, October 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.